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A Unified command and control architecture for improved visualization and decision-making on surface combatants

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MONTEREY, CALIFORNIA

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June 2009

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Prepared for: Chairman of the Systems Engineering Department in partial fulfillment of the requirements for the degree of Master of Science in Systems Engineering

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U.S. Navy organizations have implemented disparate Command and Control (C2) visualization methods for each surface combatant platform class. As a result, information uncertainty is introduced and the overall decision making process is impeded for the mission. A common architecture could resolve some of the aforementioned unsatisfactory aspects of the current situation and could also result in cost reductions. This report applied a disciplined systems engineering process to design a Command and Control Unified Architecture (C2UniArch) with focus on enhanced understanding and visualization of information. Functional analysis and modeling tools were used to validate and create estimations about performance for the As-Is systems as well as the alternatives that met feasibility constraints. An assessment was made on candidate architectures' performance and training benefits. The report was successful in demonstrating the benefits of a C2UniArch as quantified by the architecture analysis which met stakeholder and mission requirements.

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ABSTRACT

U.S. Navy organizations have implemented disparate Command and Control (C2) visualization methods for each surface combatant platform class. As a result, information uncertainty is introduced and the overall decision making process is impeded for the mission. A common architecture could resolve some of the aforementioned unsatisfactory aspects of the current situation and could also result in cost reductions. This report applied a disciplined systems engineering process to design a Command and Control Unified Architecture (C2UniArch) with focus on enhanced understanding and visualization of information. Functional analysis and modeling tools were used to validate and create estimations about performance for the As-Is systems as well as the alternatives that met feasibility constraints. An assessment was made on candidate architectures' performance and training benefits. The report was successful in demonstrating the benefits of a C2UniArch as quantified by the architecture analysis which met stakeholder and mission requirements.

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EXECUTIVE SUMMARY

Effective Command and Control (C2) is a basic requirement for the successful conduct of military missions and functions in the entire spectrum of military operations. C2 must be understood as more than a commander issuing orders; it encompasses many complex interacting elements. The inherent complexity of C2, combined with attempts to keep up with advancing technology, has led to a variety of C2 systems. This in turn has made the C2 environment more complex since each system does not do all that is required. Specifically, traditional visualization capabilities have not been adapted to deal with the complexities associated with most U.S. Navy needs, nor have they been designed to perform multiple related tasks while ensuring continuity of C2 functions supporting the mission.

The disparity of C2 systems increases the amount of operator training needed, and has an adverse effect on the operators' overall efficiency in performing their duties. The impact of disparate training results in greater operations and support costs without distinguishable improvements in overall C2 operational efficiency.

Making faster, more accurate decisions will greatly increase the effectiveness of C2 and the commander's ability to advance his objectives. Facilitating decision making is believed to be one of the best ways to speed up C2. By performing better sense making and presenting information clearly in a single comprehensive operational picture, the commander will be able to make prompt and accurate decisions. Through research and analysis, the actions necessary to achieve these objectives were revealed to consist of four major functions: Collect Information, Support Sensemaking, Plan, and Command.

Therefore, the purpose of this report is to enhance sense making and the context of the operational picture used on surface combatants (cruisers, destroyer, and frigates) by providing a standardized C2 architecture enabling common visualization. A disciplined systems engineering approach was used in order to identify requirements and design an architecture for a system that presents an understandable, organized, consistent, and focused operational picture.

Through the systems engineering process, stakeholders were consulted and research was conducted. Once the problem was better defined, a functional hierarchy was created. More specific functional and non-functional requirements were generated. Upon completion of the functional hierarchy, alternatives were generated, screened, and refined. These alternatives were then evaluated based on three key performance parameters: the time to make a decision, decision quality, decision error, the amount the new system would reduce training cost was also considered as an added benefit.

Modeling and simulation tools were used to evaluate the performance of the three key parameters. Vitech's CORE and Rockwell Automation's Arena were used to simulate the functions of the alternatives. Using the CORE software program ensured modeling of both function and data flows of each alternative. The behavior model within the CORE software also enabled evaluation and validation of the architecture throughout the design process. Using the Arena software helped quantify timing and assessed the effects of varying inputs on each of the architectures.

The three alternatives evaluated were the As-Is, the Hybrid, and the Global Understanding Network (GUN). The As-Is is an evaluation of what is currently being used; numerous stove piped systems presenting their own view of the world. The Hybrid system takes some of the information from current C2 systems and organizes and displays it in a single display. The Hybrid also retains some of the current architecture which has not been incorporated into the display methodology. The GUN replaces the various C2 systems with a more robust system where information is sorted categorically. This information can then be analyzed collaboratively by multiple operators. The information is once again shown on a single customizable display. The analysis done on this information can be shared with more context and understanding across the Global Information Grid.

The three alternatives have been evaluated on the time to make a decision, the probability of decision error, the quality of decision, as well as the resulting reduction of training required. Performance analysis results were not as expected, with only nominal gains for the evaluated measures overall. This was due to the focus of the models on the Support Sensemaking function, specifically Provide Common Visualization. Future

models should include the remaining functions and may provide more definitive performance gains. Estimates in reduced training hours for the newer alternatives were substantial. Therefore based on the gains that were discovered and the potential reduction in training hours, the recommendation is for the U.S. Navy to move forward researching the GUN system.

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I. INTRODUCTION

The design, production, and implementation of tightly integrated shipboard systems, optimized to perform a specific function, has given rise to disparate and duplicative naval platform Command and Control (C2) system implementations. There is a belief that a common C2 architecture with a standardized system approach to visualization will aid war fighters in battling uncertainty during operations. As a result of this approach, there is potentially added benefit, resulting in cost reduction of training and life cycle support.

A. BACKGROUND

Command and Control is a core piece of naval warfare in which decision making takes place and orders are generated, monitored, and guided. The goal of C2 is to advance the commander's plan leading to mission success. With that in mind, a C2 system should support the commander's intent associated with planning, directing, coordinating, and controlling the accomplishment of combat and other missions [JP 1-02]. Another goal of C2 is to be faster than the enemy in decision and execution; the next decision and action needs to be executing while the enemy is still reacting to the previous activity [NDP 6, Command and Control].

To accomplish the goals of C2 an issue surfaces because there is not a universal Command and Control system within the U.S. Navy. C2 is comprised of a number of disparate systems with each C2 system focusing on a unique aspect of the mission. There is no set of common requirements driving these multiple systems. Incongruent systems have led to a shipboard Combat Information Center (CIC) filled with visualization and decision aids with diverse graphical interfaces, semantics, and processes. A simple example of this would be the installation of Global Command and Control System – Maritime (GCCS-M), LINK-16 Tactical Display Processor and the AEGIS Display, which are installed as complete systems.

An important aspect of the disparate systems is that each system incorporates a visualization strategy that meets the narrow focus of that system. In the C2 environment

where operators and command staff must work with multiple systems to gain an understanding of the operational picture, this adds to the work load. Precious time is used to re-acquaint while moving from system to system.

This carries over to the training the operator receives for proficiency in the systems as overlap and redundant training results from trying to understand the same data on different systems. Each of the systems, based upon their architectures, requires training pipelines for both operators and support personnel at different levels of difficulty. Considering the multitude of systems, training, configuration management and sustainment costs for the U.S. Navy can be very significant.

This project concentrates on the decision making and visualization aspects of C2. This area was selected because while researching C2 it was found that improving decision making through visualization would meet most of our stakeholder’s objectives while minimizing effort required.

B. PROBLEM STATEMENT

U.S. Navy (USN) organizations have implemented many disparate systems to address different operational concepts, mission foci, and to introduce capability. Systems such as GCCS-M, Link-16 Tactical Display Processor, and AEGIS Display have overlapping functions of C2. They all present multiple visualization strategies for establishing situational awareness and decision making.

USN C2 decision making quality, accuracy, and timeliness are being negatively impacted by the implementation of disparate systems which execute overlapping C2 functions. This implementation has also resulted in high training costs. The focus of this paper is to analyze the current As-Is state and to investigate a common C2 Architecture which alleviates these issues creating a common streamlined presentation of information. Research questions that will guide research and analysis in this paper are:

- What are the functions of C2 at the surface combatant level?

- What architectures can be defined that address common requirements of USN C2 decision making, specifically related to visualization?
- Can decision making quality, accuracy, and timeliness be quantified and modeled within unified C2 architectures?
- Does a unified C2 architecture improve decision quality, accuracy, and timeliness?
- Does a unified C2 architecture reduce training costs?

Answering these questions will make the different aspects of the problem become clear and allow a conclusion to be drawn.

C. PROJECT GOALS AND DELIVERABLES

The goal of this project is to analyze the current visualization elements of the U.S. Navy C2 architecture on the surface combatant platform and as they relate to decision and sensemaking. Furthermore, it performs research and develops unified architectures that combine the disparate C2 visualization strategies and improve U.S. Navy C2 elements of decision and sensemaking. Finally, it provides analysis on decision quality, accuracy, and timeliness to examine if unified architectures improve USN C2 decision and sensemaking requirements.

This report documents the C2 functional hierarchy with emphasis on sensemaking and, more specifically, contextualization. This report also documents an in depth analysis of the As-Is state and two new architectures that improve decision quality, accuracy, and timeliness.

D. ASSUMPTIONS AND CONSTRAINTS

This paper examines alternate architectures for Command and Control systems with a focus on visualization with the goal of reducing decision making time and uncertainty. This paper will only examine the aspects of C2 which directly affect the

decision making process. All other aspects of C2 supporting the same stakeholder need have been left for later study.

The ship classes being considered are U.S. Navy surface combat ships excluding carriers. Two mission threads were considered Search and Rescue and Cruise Missile Defense. These were used to help define the alternate architectures and define performance measures.

E. SYSTEM ENGINEERING AND DESIGN PROCESS

1. Overview

The tailored System Engineering Design Process (SEDP) applied for this project used an iterative design approach composed of three phases: Problem Definition, Design and Analysis, and Architecture Analysis. It was the primary means used to define the C2 requirements and desired architectural baseline required by the U.S. Navy. An examination of the waterfall, classic Vee, and spiral system engineering processes were conducted to determine the best approach for this problem [Blanchard and Fabrycky, 2006]. It was determined that a modified SEDP process as shown in Figure 1, derived from Sage & Armstrong's' Life Cycle of System Engineering, and the United States Military Academy (USMA) system engineering process, was the best approach [Sage and Armstrong, 2000]. These processes were combined in order to highlight the key ideas from Sage and Armstrong and also emphasize some important DoD methodologies used by USMA. The architecture analysis phase was modified to show architectural analysis recommendations have been made but a Life Cycle Cost Estimate has not been completed.

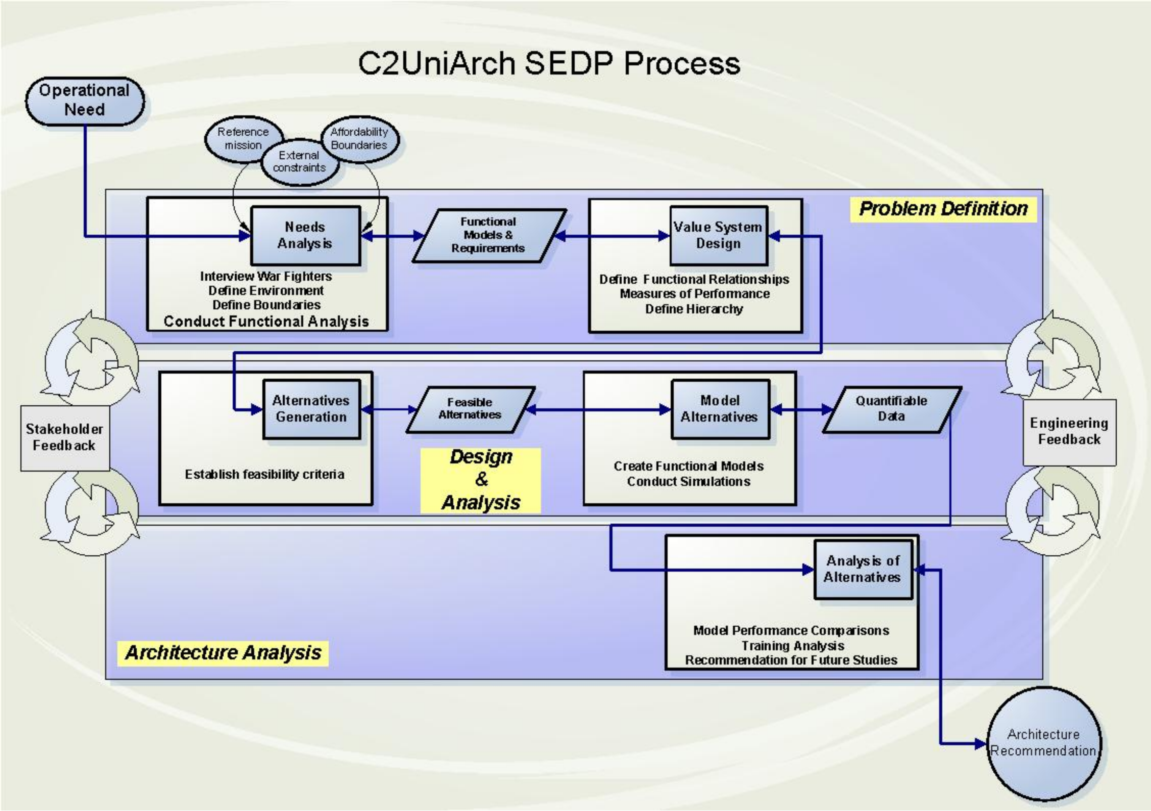

Figure 1. Tailored SEDP Diagram

The tailored systems engineering design process developed by the C2UniArch team combined processes from USMA and Sage & Armstrong's life cycle of system engineering.

2. Problem Definition Phase

This phase was an iterative process allowing Stakeholders' objectives to be refined into a well-defined problem. The Problem Definition phase helped narrow down a loosely defined problem statement into a well-understood problem meeting stakeholders' needs. The output of this phase was a clearly defined problem statement that was used to generate requirements.

a. Needs Analysis

The Needs Analysis is essential in determining the true nature of the problem along with the desired outcomes of the problem's solution. Due to C2 being a complex and intricate domain a great deal of research was needed along with numerous

conversations with our stakeholders from the warfighter community. Research and discussion removed the layers of obscurity surrounding the initial problem statement allowing it to be transformed from wants into stakeholder requirements and an effective need. Also, in this section the system context including system inputs and outputs were identified.

b. *Functional Analysis and Decomposition*

Upon completion of the stakeholder analysis, a functional analysis and decomposition were necessary to transform the functional, performance, interface and other needs that were identified into an organized and consistent hierarchy. Functional decomposition took the identified high-level functions of C2 and broke them down into more easily understood sub-functions. This broke the complex C2 problem space into more manageable sub-problems. Thus, this phase focused on answering the question, "What are the functions of C2 at the surface combatant level?"

In this part of the SEDP functions were researched that aided in understanding the situation and creating awareness. This includes making connections between different data types and communicating these connections effectively to various personnel.

c. *Value System Design*

The Value System Design started with the stake holder objectives being examined in parallel with the functional and non-functional hierarchies. This is done in order to further link the problem to the stakeholders' objectives and determine the value of each design element. Evaluation measures were then identified. Key evaluation measures were then selected from those identified. These evaluation measures needed to be quantifiable and extractable during modeling in order to be used for evaluation of alternatives.

3. Design and Analysis Phase

a. Alternatives Generation

Alternative architectures were created to assess the impact of commonality of information display on C2 performed on surface combatants. Using the list of evaluation measures from the Value System Design, research was conducted to determine if alternative architectures existed which met system requirements. Candidate alternatives which were deemed feasible were selected for further analysis. The output of this phase was two architectures selected for further analysis through modeling and simulation.

b. Model Alternatives

The selected architectures were modeled. Simulations were built using ARENA simulation software for the proposed architectures to aid in the decision making process. The simulations yielded quantifiable results which allowed the value of each alternative to be objectively assessed. The data yielded was to measure each alternative in terms of its performance against the chosen evaluation measures.

4. Architecture Analysis Phase

a. Analysis of Alternatives

In this segment, the alternative architectures were examined against the each other and the As-Is architecture. The input to this section was the results of the modeling and simulation along with additional information available on the proposed architectures. A variety of analyses were conducted using the modeling and simulation results to create a true mock up of the alternatives. During this phase, other benefits were examined which were more indirect in nature including those associated with the logistical aspects of the architecture. The output of this section provided in-depth results that help lead to a recommended architecture.

b. Architecture Analysis Recommendation

As a culmination of the analysis performed in the previous phases, the Architecture Analysis Recommendation step provided quantified data on the alternative system architectures. After summarizing the analyzed data, this step presented a recommendation on how to proceed. The main purpose was to recommend how the problem is best solved based on the information found and analyzed.

II. PROBLEM DEFINITION

The initial phase of the Systems Engineering and Design Process (SEDP) known as Problem Definition is the exploration of the original problem statement. This phase is an iterative process to ensure all aspects of the problem were identified, understood, and agreed upon by all stakeholders before entering the Design and Analysis Phase, the second phase of SEDP. This phase was comprised of two iterative steps: Needs Analysis and Value System Design. Two additional tools aiding in problem definition were used, functional decomposition and flow analysis. The final output of the problem definition phase was an understanding of the problem in the form of clear and unambiguous requirements meeting stakeholder objectives. To ensure clarity, the problem was then articulated in the form of a refined engineering problem statement.

A. NEEDS ANALYSIS

The first step in this phase was the Needs Analysis, which involved the use of various tools for identifying and outlining the system under study; the relevant stakeholders; and the stakeholders' needs, objectives, requirements, and constraints. The products from the needs analysis are a list of system objectives as stated by the stakeholders and a functional decomposition. The goal of needs analysis was to transform the primitive need stated by the stakeholder into an effective need to be used in the next stage.

The primitive need was understood to be:

> The [U.S.] Navy's Command and Control (C2) strategy does not have a common set of C2 requirements that can be used across multiple surface ship platforms. There is a need to define a common set of C2 requirements to support the creation of a common enterprise level C2 architecture while considering emerging service-oriented architecture technologies.

1. Background and Context of Maritime C2

Conducting background analysis and establishing context of maritime C2 assisted in the understanding of the system. It provided a look at the system in terms of its interactions with other systems and the environment, inputs and outputs, and overall

operation. From understanding the system in this perspective, deficiencies were identified and the gap between the current state of the system and the desired end state of the system were made clear. This was an iterative process further defining the system on each pass to eliminate the identified deficiencies and achieve proper interfaces.

Understanding the problem required stepping back and examining the definition of C2 and determining if it could be the basis of the overall requirement. The definition of C2 from Joint Publication 1-02 is:

> The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission [JP 1-02].

This definition established a foundation for exploring and providing a basic idea of how C2 should be executed. This highlighted the system must be able to support the direction and coordination of a military effort. But it did not clarify if this also applied to all platforms, including surface combatants. It was further discovered C2 is a complex subject and not well understood by many.

> To add to this perspective, C2 was not limited to military organizations and involves thinking, sensing, responding, organizing, and monitoring also, and therefore was composed largely of activities in the cognitive and social domains [Alberts et al., 2001].

The complexity of C2 and all of its definitions has exacerbated the ability to create systems that support surface combatant commanders. Classic surface platforms were built with systems that were unitary in supporting well-defined combat mission tasks. Missions such as Anti-Submarine Warfare, Anti-Air Warfare and Anti-Surface Warfare have been tightly coupled into a surface combatant system. The C2 Systems, Applications & Afloat Networks resource sponsor, OPNAV N6F2, asserted that expectations have expanded to include missions that are not well defined and may include wartime and peacetime operations [Beck, 2009]. This has resulted in the need to access information from varying sources in many formats. A recent example was the U.S. Navy's efforts to improve the nation's Maritime Domain Awareness (MDA), which was

deemed critical in the global war on terrorism. Also, the Automatic Identification System (AIS) was mandated by international law for ships with Gross Tonnage of 300 or more tons [Department of Homeland Security, 2006]. AIS is a shipboard display and broadcast system. It is used by maritime activities and provides a means for ships to electronically exchange ship data, including identification, position, course, speed, port of departure, destination and supposed cargo [Department of Homeland Security, 2006]. Upon implementation of AIS, legacy U.S. Navy systems struggled to obtain and display this data [Klich, 2008].

Research revealed concerns about the ability of the war fighter to properly interpret the vast amounts of data being exposed. Information is key to lowering uncertainty and is critical to effective decision making. Therefore, advanced techniques for supporting the military commander and displaying complex tactical situational data in a clear way must be analyzed. A part of C2 is the output and presentation of tactical information. It has a large influence on the general decision making process because the commander's mental model of the battle space situation is based upon the information received and how information is perceived [Miller and Shattuck, 2004]. C2 is not just a process of putting seemingly unrelated items on a map.

2. Stakeholder Analysis

Nuseibeh and Easterbrook define stakeholders as "individuals or organizations who stand to gain or lose from the success or failure of a system" [Nuseibeh and Easterbrook, 2000]. To ensure the quality and comprehensiveness of system design, it was important to identify all relevant stakeholders and include them throughout the design process. The stakeholder analysis enabled a collaborative cooperation between the team and those individuals who were able to articulate what was required by the system and the performance expectations thereof.

The resource sponsor, Office of the Chief of Naval Operations (OPNAV), is responsible for a collection of resources that comprise inputs to warfare and supporting warfare tasks by planning and identifying the funding for the requirements. A common

C2 architecture provides a potential savings in overall budget profile by reducing individual specific C2 designs. The Program Sponsor is yet to be determined, as it depends on program initiation.

The execution agents and systems commands would be responsible for the development and acquisition of the architectural baseline and establishing the life cycle support of the system to be fielded. Representatives from the Program Executive Office Command, Control, Communications, Computers, and Intelligence (PEO C4I) and Space and Naval Warfare (SPAWAR) Systems Command were used to provide feedback on the architectural soundness, maintainability, and supportability of the design. Program Executive Office Integrated Warfare Systems (PEO IWS), which is responsible for surface ship and submarine combat systems, missiles, radars, guns, and electronic warfare systems, was also identified as a stakeholder.

The war fighting community drives the requirements for the common C2 architecture. Its tactical and operational experience is essential in providing data for this architecture. This in turn provides benefits to the war fighter, which enhances mission execution. To ensure this community interest has been taken into consideration, representatives from U.S. Naval Forces Pacific and Central Command, Joint Information Control Officers (JICO) were heavily consulted. The JICO is responsible for planning and management of the joint tactical data link network within a theater of operations and has unique insight to C2 expectations of the platform from the commanders' level. Due to the nature of this problem, it was important this community's interest was well understood. To enable a better understanding of this community's perspective, C2 analysts with prior war fighting experience were consulted.

It was important to understand the perspective of each of the stakeholders. The analysis of existing documentation, such as organizational charts, doctrine, and manuals of existing systems was undertaken to get perspective on the stakeholder environment. Forward-thinking sources such as the Command Control Research Program (CCRP) were also researched. Semi-structured interviews were conducted and followed up with questionnaires shown in Appendix C. The questions that resulted from the research were

seen as a good way of starting a conversation with stakeholders. Stakeholders were consulted throughout the entire systems engineering process.

a. Stakeholder Interviews

The OPNAV representative confirmed the U.S Navy's Command and Control strategy does not have a common set of C2 requirements used across multiple surface ship platforms. CAPT Rick Beck, from OPNAV N6F2, recognized the difficulty in quantifying a gain in force effectiveness achieved by Command and Control. Unlike a ship, a plane or a missile, how much C2 is needed to facilitate mission success is difficult to quantify. War fighter interviews revealed related concerns. CAPT Rick Beck further added, "one system design across multiple platforms should yield efficient training, configuration management and sustainment costs" [Beck, 2009]. CAPT Anderson, a battle watch captain from U.S. Naval Forces 5th Fleet, mentioned that it seemed logical the lack of a common architecture was possibly a contributing factor to a perceived lack of understanding of what C2 really provides [Anderson, 2009]. Finally, it was cited by the PACFLT N35 JICO that a common C2 architecture should enhance interoperability across different ship classes across the fleet. "Most DDGs and CGs fail to realize just how much they contribute to the C2 picture and ADM Willard's goals" [Cetello, 2009].

b. Stakeholder Desired System Needs

Through the stakeholder analysis, high-level qualitative system goals desired for a common C2 system were derived. It was important to understand and categorize the different types of requirements as they were captured from the stakeholders. Most important, the team needed to understand what the system was expected to accomplish within its environment. These were categorized and analyzed into functional requirements in the Functional Decomposition section.

The below numbered list is the desired system objectives. The objectives highlighted in bold address stakeholder needs with regard to the situational awareness, system complexity, and decision support problems. These were used as a foundation for later functional analysis.

1. Provide the capability to gather information supporting mission objectives in a timely manner

2. Provide the capability to assess the quality of the sensor and intelligence data

3. Support the capability to interface with legacy local organic and national ISR sensors

4. Provide for a cost effective approach for new interfaces

5. **Provide the capability to create a common understanding of the situation to include location, identity, status and intentions of friendly, hostile, neutral and non-military entities historically, currently, or planned reducing decision delays**

6. **Provide the capability to display political and diplomatic information via a map interface**

7. **Provide the capability to improve situational awareness by creating associations between different sources of data, if applicable**

8. **Provide the capability to share information with Blue forces in near-real-time**

9. **Provide the capability to alert on events that are geospatial or informational**

10. **Provide the capability to display current and forecasted weather information**

11. Provide the capability to lay down objectives and work out alternative means for attaining them

12. Reduce information assurance vulnerabilities

13. Provide the capability to maintain situational awareness in a disconnected or electronically denied environment

14. **System interface should be intuitive and interface should reduce operation complexity**

3. Environment Definition

a. Surface Combatant

Surface combatants include cruisers, destroyers, and frigates. They are primarily designed to fight in the open ocean in one of three warfare areas: anti-surface, anti-subsurface, and anti-air. Modern surface combatants are all equipped with sensors and engagement elements which enable appropriate action in all warfare areas. The definition includes other vessels, such as the littoral combat ship and the battleships of yesteryear. Aircraft carriers, amphibious ships, and some smaller vessels, such as mine-warfare ships and patrol craft, are not included in this study [Congressional Budget Study, 2009].

b. System Environment

The environment where the system will be installed includes the CIC, the bridge, staff spaces, and intelligence spaces. These environments are well maintained and away from the harsher elements that would be a consideration for systems directly exposed to the exterior of the ship or other spaces indirectly exposed such as engineering or the hanger bay.

Despite the expected environment as described above, the system still needs to meet specific military shipboard requirements to be combat ready. Consideration for shock, vibration, interference, grounding, and power must be given. For the remainder of the report, it is assumed that any alternative can be designed to these standards.

c. Organizational Structure

Surface combatants' capabilities make them well suited for a variety of force structure mixes. The multi-mission packages, and the sheer number of CGs, DDGs, FFGs, and soon the DD(x), enable the U.S Navy to utilize the platforms in most tactical force structure packages. As depicted in Figure 2, the surface combatant can be used in the following compilations supporting the Joint Force Maritime Component Commander (JFMCC) operational cell called the Maritime Operations Center (MOC): Carrier Strike Groups (CSG), Expeditionary Strike Group (ESG), Coalition Operations, and Surface Action Groups (SAG) [NNWC Tacmemo 3-32-06]. All of the tiers of organizational structure benefit from a C2 architecture. The Commanding Officers and operators from each platform directly benefit from the local C2 system and exercise it tactically. Not only is the Surface Combatant C2 architecture a fundamental aspect of shipboard operations, the output contributes to the organization knowledge of the battle-space at higher levels.

"Commanders then must compare their situation awareness and assessments of what is required to advance the plan with the actions of their subordinate commanders and act—remembering always that their goal is to contribute information and perspective that are not already evidenced" [Willard, 2002].

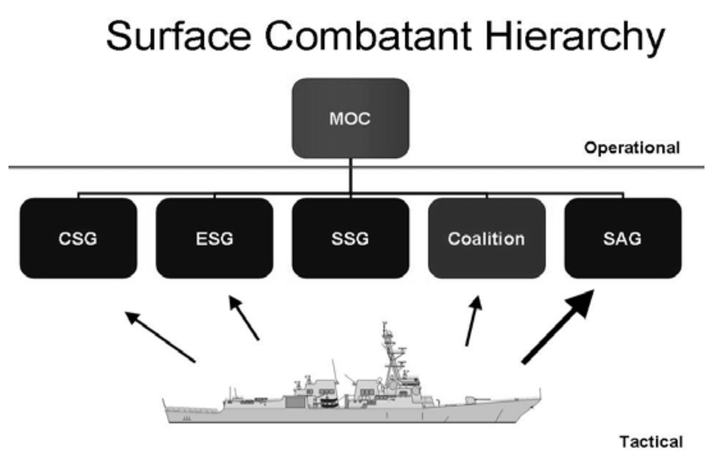

Figure 2. Surface Combatant Hierarchy

The naval Surface Combatant Hierarchy includes the Maritime Operations Center and its tactical structures, such as Carrier Strike Groups, Expeditionary Strike Groups, Surface Strike Groups, Coalitions, and Surface Action Groups.

4. System Boundary

Once the investigation of the environment was completed, it was necessary to put the system into context. Identifying the boundary of the system aided in the understanding of what the inputs, outputs, and controls were for the Common C2 architecture. This is demonstrated in Figure 3.

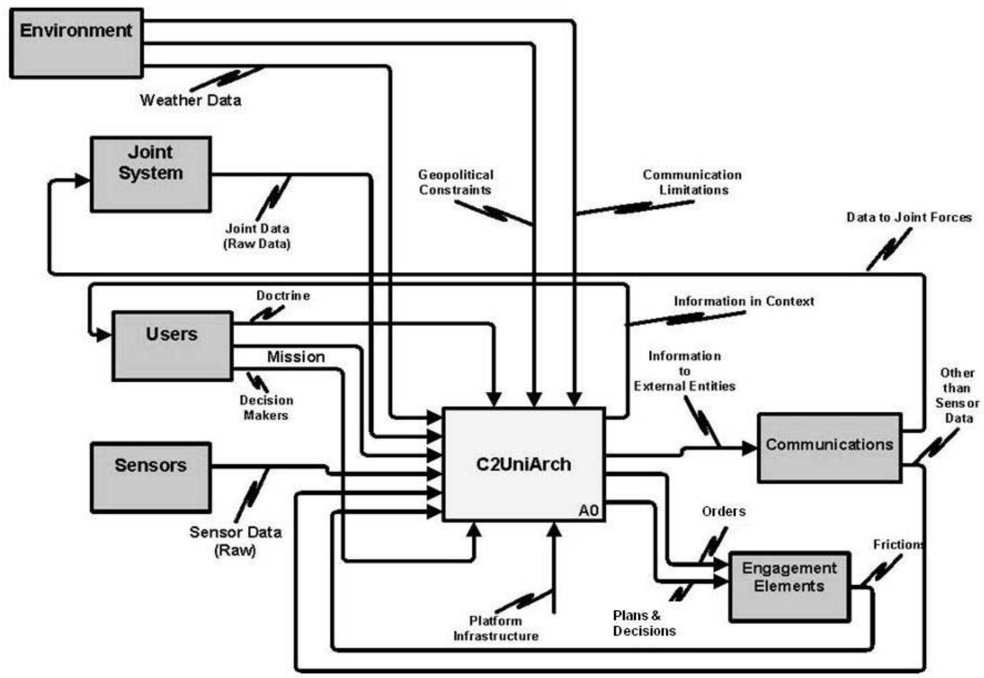

Figure 3. System in Context (A-1)

The development of the system boundary diagram (A-1) aided in putting the C2UniArch system into context. The inputs of the Common C2 are raw data and mission tasking while the output can be a decision, direction, order, or authority. Controls which are geopolitical factors, doctrine, and CONOPS are shown on the top.

The inputs, shown in Figure 3, are very important because they start the C2 function and get transformed into the output. External interfaces to the system are Joint Systems, Users, Sensors, Communications, and the Environment. The system interacts with DoD Joint Systems in terms of relevant data and information exchange to supporting surface combatant missions. The Users interact with the system by providing the current mission and applying doctrine. Sensors provide data. Communications provides a path to

receive and transmit information and is relevant to mission success. The fundamental output of the system is an order, decision to take action, or communicated intent via a plan to engagement elements. This output may be a decision or communication to do nothing. Frictions in this case would represent feedback into the system if the orders did not execute according to plan. With respect to the environment, the system does not necessarily interact with it; however, the system is impacted or limited by the environment.

To summarize the Needs Analysis segment of the Problem Definition, the team was able to identify the nature of the problem. Navy organizations have introduced unique approaches to expose new information sources leading to disparate processing and presenting of the information needed. Research revealed complication and confusion about what Command and Control is and how it can be accomplished. The complexity of C2 and disparate architectures combined, potentially impact situational awareness and cause delays in the decision making process. These issues were discovered as not only present across surface combatant classes, but within the platform itself.

The effective need is used to guide the identification and examination of various components needed to establish metrics to measure successful completion of the report. It was created through iteration, vision and feedback during the processes utilizing Stakeholder Analysis, and problem examination.

It was initially proposed that a common C2 architecture would be a solution to the unfavorable state. This paper examines if this is qualifiable and quantifiably accurate in the subsequent sections using the effective need as a guide. The effective need is stated below:

"The U.S. Navy needs a flexible, reliable, easier to learn, surface combatant C2 architecture that supports communication, storage and display of relevant, information to commanders to facilitate efficient understanding and effective decisions for mission accomplishment"

The extent of the capstone project was assessed, and an understanding that all of the aspects of C2 would be difficult to cover. As a result, with stakeholder agreement, boundaries were established for this study to focus only on the decision making aspects of C2. Meeting with stakeholders, aided in identifying top level needs, which were drawn upon during the Functional Analysis and Decomposition stage.

B. FUNCTIONAL ANALYSIS AND DECOMPOSITION

Once the problem was understood, stakeholders interviewed and needs articulated, a functional analysis was performed to understand the potential architecture from a functional perspective. This approach allows for the architecture to be designed independently of any specific solution. A functional decomposition provides reasons for the different alternative components selected to implement the architecture. Analysis of the system in functional terms provides a foundation for developing original alternatives [Sage and Armstrong, 2000].

In order to start the functional analysis, examination of what the system needs to accomplish was conducted. This generated the basic question, "what are the functions of C2 at the surface combatant level?" To answer this question, a simplistic process model of C2 was needed, creating a framework and supporting the effective need.

Research has shown Boyd's OODA (Observe-Orient-Decide-Act) loop is clearly the dominant model of C2 and has morphed into various interpretations of the kill chain [Boyd, 1987]. Basically, the models all use the basic approach described in Figure 4. Fundamentally, these functions support planning, directing, coordinating, and controlling the accomplishment of combat and other missions.

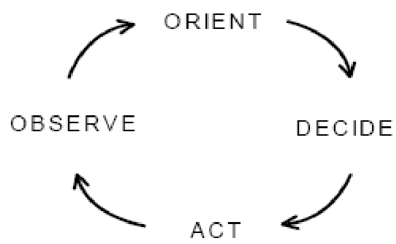

Figure 4. Boyd's OODA Loop

A representation of the flow of the OODA loop is shown here. The flow of the OODA loop model applies to the combat operations process [Boyd, 1987].

The complexity of C2, and the problem as described by the stakeholders, forced the evaluation and consideration of not just what C2 was, but should be. Brehmer claims the OODA loop was too basic for today's warfare. Brehmer adds the OODA loop does not include a representation of the environment and the affects of the decisions, arguing uncertainty and delays need to be taken into account, making the loop more dynamic. A more advanced interpretation was the Dynamic OODA loop, depicted in Figure 5, or DOODA loop, and specifies three different needed functions: data collection, sensemaking, and planning. Incorporating these effects into the loop constitutes a fundamental shift in focus from the traditional conception of C2 as "inward looking and concerned with handling the force (as embodied in definitions of C2), to a conception of C2 as outward looking and being concerned with achieving effects" [Brehmer, 2005].

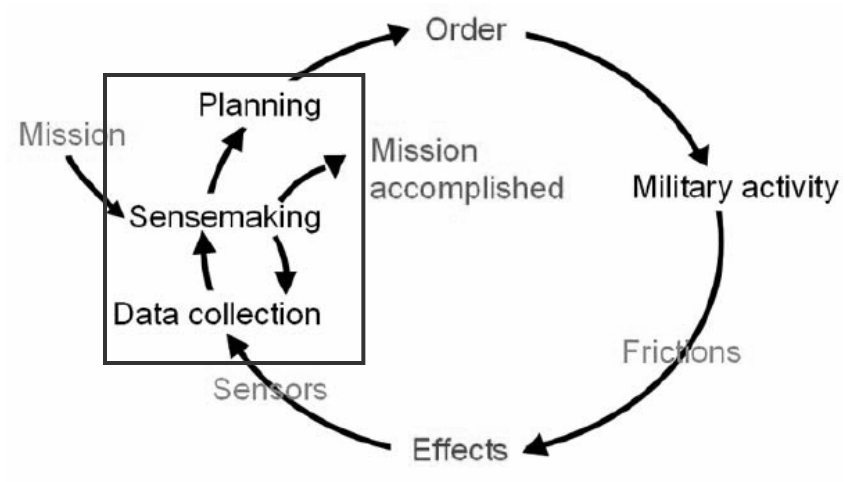

Figure 5. Brehmer's DOODA Loop

The dynamic OODA Loop. The modification to the OODA loop addresses the dynamic elements that influence the model. The items in black are functions that are logical relations that establish preconditions for the next function. The box highlighted contain the three fundamental function used from the loop [From Brehmer, 2007].

The DOODA loop decision making process model was determined best suited to create a framework to meet the effective need. The unified C2 architecture synthesized three fundamental functions from this model for surface combatants: Collect Information, Support Sensemaking, and Plan, to support the overall system objectives. A Command function was added to represent the order and military activity portion of the model. Figure 7 represents the high-level surface combatant C2 system internal functions needed to support stakeholder objectives. The inputs, outputs, and controls are the same as shown in A-1 in Figure 3.

Figure 6 shows the transformation of the OODA loop into the C2 functions examined in this report. The left depicts the OODA loop. Next in the center, the DOODA loop is displayed with some additional annotations. The center shows a box around Planning, Sensemaking and Data collection, and another box around Order. The box around Planning, Sensemaking and Data Collection is to show that these functions came from Observe, Orient and Act from the OODA loop. Additionally in this paper, these functions make up the bulk of the C2 Functions which are Collect Information, Support Sensemking, and Plan. The box around Order is labeled Act. This is to point out that Act from the OODA loop has been partially absorbed into Order in the DOODA

loop, however part of Act is now a part of Military activity in the DOODA loop. In Figure 6, when transitioning from the DOODA loop to the C2 functions on the far right, Act and Order are not present. The functionality represented by these functions is replaced by Command. The rest of the DOODA loop including Military activity, Frictions, Effects, and Sensors are recognized as important functions and are still considered part of the battle space but are not considered Command and Control functions.

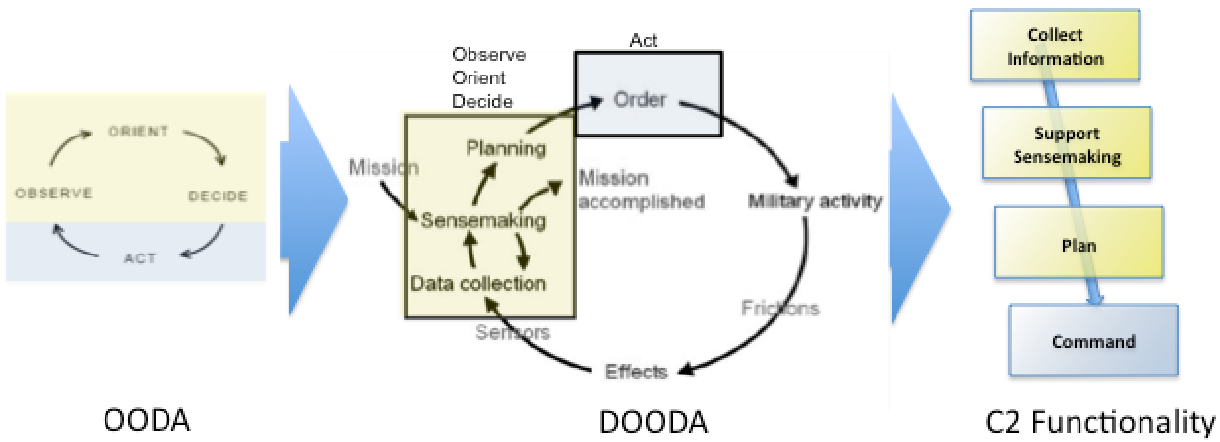

Figure 6. Transition of the functions of C2

Analysis of the traditional models enabled synthesis of the core functions of Command and Control. Starting with the OODA loop, exploring the enhancements of a more advanced DOODA loop established four fundamental functions needed.

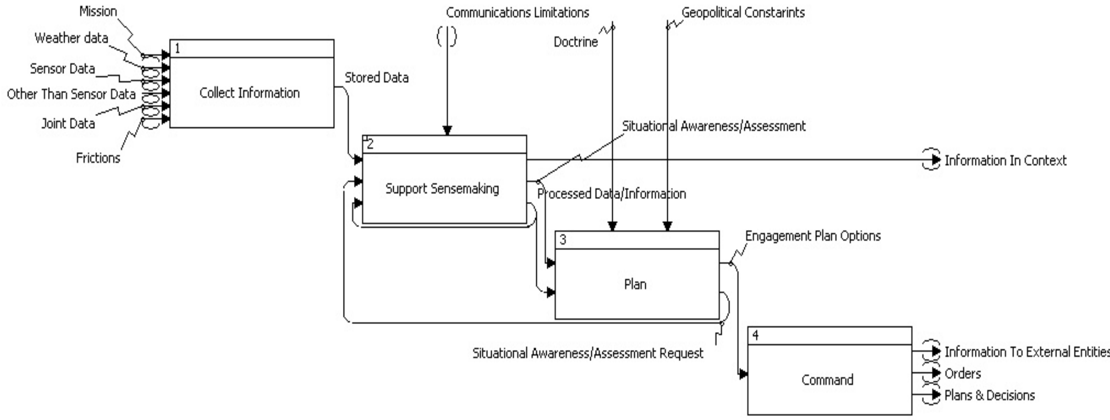

Figure 7. IDEF A0 Functional Representation of the C2 System

Further decomposition of A0 shows four essential functions required for a Common C2. These four functions are Collect Information, Support Sensemaking, Plan, and Command. Interactions of these functions transform data and information into a decision.

1. Collect Information

The function Collect Information must not be confused with the Observe portion of the OODA loop for the C2UniArch. Collecting information has multiple tasks. As shown in Figure 7, Collect Information, derived from Data Collection in the DOODA loop, illustrates that data collection is to provide a point for raw data from sensors and information to flow into the system and does not include the sensors but may include the tasking of sensor resources. The outputs of sensor systems are raw data. This raw data provides the input for the data collection portion of the DOODA loop. The Collect Information function for the common C2 system defines information transfer requirements for effective decision making and supports the sensemaking function. This does not include the sensors themselves or represent the monitoring or localizing of any targets. This function's purpose is to obtain data from any available sensor or data service relevant to the mission being conducted. Because of the vast amounts of data from sensor information, national and human intelligence, weather, Joint information, and various forms of report from subordinates, the function must be able to allow the decision maker to tailor or filter information to cope with data overload. The downside in this approach is "it is not obvious to the decision maker which data have been excluded by the

individual's preferences. In addition, individuals may have different preferences selected, resulting in "divergent and possibly confusing views of the environment" [Shattuck and Miller, 2004]. Understanding this drawback, the function allows the decision maker to subscribe to the data needed for the mission and provides an alert if data is available to meet some desired criteria. To support the objective, this function stores historical or planned target data for future analysis. Stored data allows for the ability to maintain state in the event the platform was disconnected from its communication path or it was being electronically denied. The output of this function would feed the data requested to the Sensemaking function. The system needs stated from the stakeholders map to the collect information function are listed in Table 1.

Function	System Objectives
Collect Information	Provide the capability to gather information supporting mission objectives in a timely manner
	Provide the capability to assess the quality of the data
	Support the capability to interface with legacy local organic and national ISR sensors
	Provide the capability to maintain SA in a disconnected or electronically denied environment

Table 1. Collect Information Function Objectives

The Collect information function is part of the C2 system and supports the sensemaking function. Its objectives come from the stakeholder requirements to include the ability to assess the quality of data, maintain SA, and create a common understanding of the situation.

2. Support Sensemaking

Sensemaking is defined as a function with the aim of producing an understanding of the mission in terms of what needs to be done to accomplish the mission [Weick, 1995]. This function aids the decision makers in making sense of the information and the situation. It involves many phases of knowledge processing of which the majority is cognitive. This function is at the core of the problems stated from our stakeholders and is key to addressing situational awareness issues. This concept was best summarized by Perla, "it's knowing what's going on so you can figure out what to do" [Perla et al., 2000].

Theorists suggest the ability to make a decision by lowering uncertainty can somehow be ensured in warfare by adding more data via sensors [Owens, 2000]. In addition, an increase in the quantity of data offers no advantages if the quality of data has been compromised. The Support Sensemaking function recognizes that an increase in information may increase ambiguity. If this ambiguity is not properly addressed, it may impede the decision making process. In the 1973 Yom Kippur War, the failure of Israeli intelligence to foresee the Egyptian and Syrian attacks was not due to a lack of information but to the misunderstanding of the information available in the context of an inappropriate shared awareness of Arab intentions [Bolia, 2004].

In order to address the issues mentioned and meet system objectives, the following section will focus on this function and will be further decomposed. The system needs stated from the stakeholders map to the support sensemaking function are listed in Table 2.

Function	System Objectives
Support Sensemaking	Provide the capability to create a common understanding of the situation to include location, identity, status and intentions of friendly, hostile, neutral and non-military entities historically, currently, or planned reducing decision delays
	Provide the capability to display political and diplomatic information via a map interface
	Provide the capability to improve situational awareness by creating associations between different sources of data, if applicable
	Provide the capability to share information with BLUE and Coalition units in near-real-time.
	Provide the capability to alert on events that are geospatial or informational.
	Provide the capability to display current and forecasted weather information
	System interface should be intuitive and interface should reduce operation complexity

Table 2. Support Sensemaking Function and Objectives

The Support Sensemaking function is the core of the issues stated from the stakeholders and is the key to addressing SA issues. The objectives are aimed to aid the decision maker to try to make sense of the information and situation through many phases of knowledge processing.

A functional hierarchy of the Common C2 in Figure 8 shows the Support Sensemaking function and its sub functions. The sensemaking function was central to addressing the decision making process and is key to transforming data into information

and supports understanding. The three sub functions of the Support Sensemaking function are Collate and Correlate, Provide Contextualization, and Share Information.

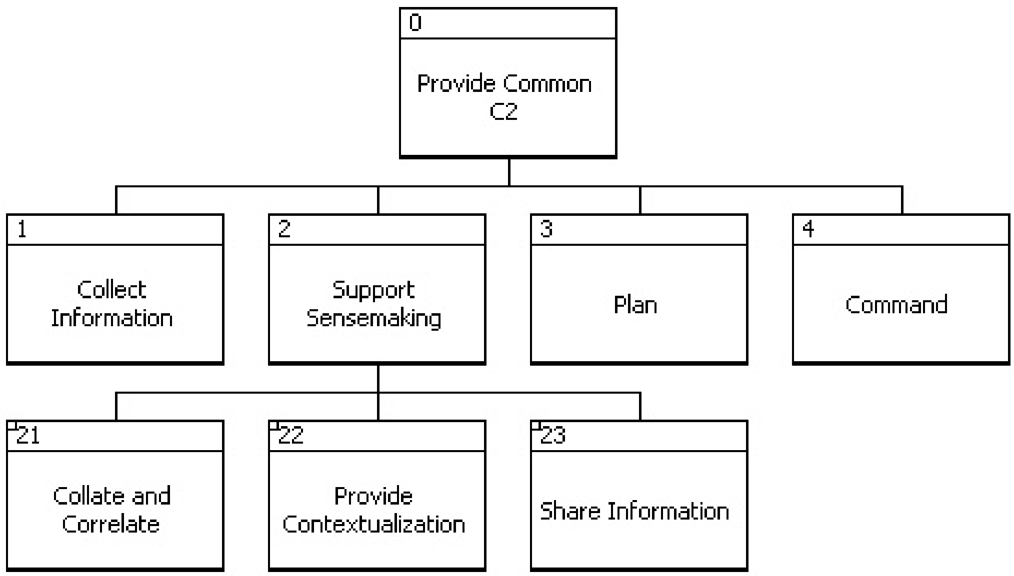

Figure 8. Support Sensemaking Functional Representation

The Support Sensemaking function is the key function identified from this study based on the stakeholders' priority needs of Common C2 functions. It also shows how it relates to its sub functions which are Collate and Correlate, Provide Contextualization, and Share Information. The other functions were not decomposed because they did not directly impact the decision making phase.

a. Collate and Correlate

Decomposing Support Sensemaking yielded three functions and multiple sub-functions. Figure 9 displays the decomposition of Collate and Correlate. The Collate and Correlate function defines what must be done to the data once it is received. This function was broken down into two sub-functions: Organize Information (Collate) and Link Related Items (Correlate), as represented below.

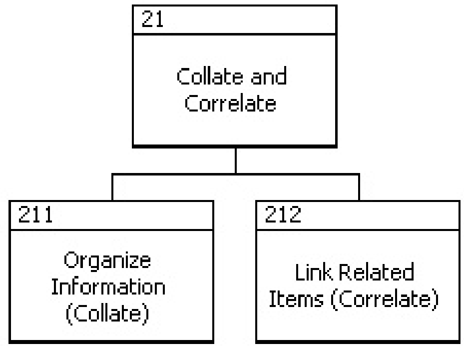

Figure 9. Collate and Correlate Functional Representation

The Collate and Correlate function is where information is sorted, organized, linked, and associated. The output of this function is fed into the Provide Contextualization function, where the information is contextualized.

The Organize Information (Collate) sub-function is where the received data is organized into operational and tactical information so decisions can be made. Once the information is organized accurately and concisely, the data is then compared to other critical elements of information so the decision maker can easily verify what he or she is observing.

The next sub-function associated with the Collate and Correlate function is Link Related Items (Correlate). In the Link Related Items sub-function, information is screened for meaningful relationships, connections, and relevancy to aid the understanding and analysis of the decision maker.

b. Provide Contextualization

Provide Contextualization, shown in Figure 10, is the function that establishes a set of norms for the system and the operator that puts events in perspective of each other [Smith, 2005]. This is a key function allowing the user to gain understanding of the data. Understanding requires a fusion of awareness and context to establish meaning. This requires integration of numerous elements of the situational picture that vary over time, establishing patterns matching expected behaviors [Marsh, 2000].

This function may also be commonly understood as a way to provide situational awareness. "Situation awareness was the perception of the elements in the environment

within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [Endsley, 1995]. This function is supported by three sub-functions: Establish Knowledge of the Battle Space, Provide Common Visualization, and Alert on Pattern or Anomaly.

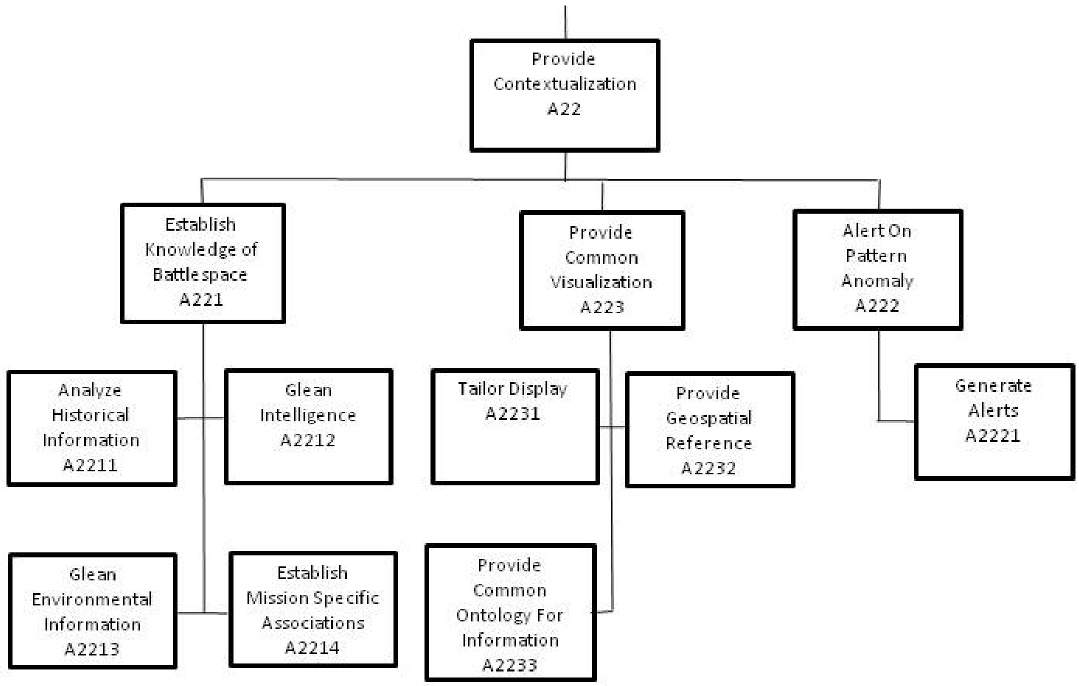

Figure 10. Provide Contextualization Function

The Provide Contextualization function is also known as a means to provide SA. It is the key function that allows the user to gain understanding of the data.

Establishing knowledge of the battle space is the function that recognizes "a decision maker's knowledge of the environment can be no better than what has been detected by the sensors at any given point in time; understanding can be no better than the data they are able to access" [Shattuck and Miller, 2004]. The function is supported by several sub-functions to aid in gathering this knowledge. Analyzing Historical Information (A2211) is the sub-function that establishes the building block for deciphering complex scenarios, e.g., when and how often an event has happened before. Historical information can also be used as a feedback mechanism for analysis and assess ongoing cause and effect chains.

In order to support system objectives, Glean Intelligence (A2212) is needed to understand historic and current, planned, hostile, neutral or non-governmental agencies actions. Intelligence is the product resulting from the collection, processing, integration, analysis, evaluation, and interpretation of available information concerning foreign interests, including information and knowledge about an adversary obtained through observation, investigation, analysis, or understanding [JP 1-02]. This function is to provide the commander with an accurate understanding of the threat situation as it relates to current and future operations. It does not include the acts of gathering intelligence; just a reaping of the data already gathered and analyzed supporting the mission at hand.

Glean Environmental Information (A2213) is to support the objective to display any meteorological or oceanographic phenomenon that will impact sensor, weapon, or mission performance.

The Establishing Mission Specific Associations function (A2214) is an important aspect to the contextualization function. This function establishes disparate elements or events that can be related to one another based upon observations over time. This function would allow the operator to create these relationships to aid establishing knowledge of the situation and to flag disparities for manual resolution of ambiguity. This may also include projections for future events. These relationships may be made between objects displayed and tasks or mission interests, for example, creating an association between a ship's Area Of Responsibility (AOR), enemy range, and areas of strategic advantage for both friendly and enemy forces.

The Provide Common Visualization function facilitates understanding of the current situation as well as the mission. It provides an effective method to present information and data to the user to support the sensemaking process.

The Provide Common Visualization function is comprised of three sub-functions, the first of which is Tailor the Display (A2221). "The capability to tailor what is displayed is one way designers may attempt to assist decision makers in coping with data overload. The drawback in this approach is that it is not obvious to the decision maker

which data have been excluded by the individual’s preferences” [Shattuck and Miller, 2004].

Providing Geospatial Reference (A2222) is the function that gives the operator and commander a point of reference. The most common interpretation of this function is a map with overlays to portray the battle space. However, other means of geospatial displays could be created.

The final sub-function for common visualization is Provide Standard Ontology for Information (A2223). This function establishes the standards for the visualization elements. This function was added to address interoperability as a functional aspect of the system. "In stove-piped systems, semantics are in the mind of humans. Humans must resort to catalogs and other natural language documentation to interpret the meaning of system outputs, and must perform labor-intensive, manual transformation to interchange data between systems" [Laskey et. al, 2001]. This function also ensures that when operators are viewing the system, there are familiar elements to the information being displayed. Textual information follows themes. Tracks or objects will display common attributes and follow a standard symbology and color scheme. Multiple sensor ontology combined in a single format can increase understanding of message content and provide commanders reference material for selecting the right platforms from which to retrieve data [Ceruti, 2004]. Common ontology can simplify training by establishing predictability of the user interface and can also aid in decreasing uncertainty of the decision maker.

The Alert on Pattern or Anomaly (223) is a function with the purpose of aiding commanders in identifying any events of interest based upon some set criteria. Events could be based upon mission criteria or status of the systems in use. Preset rule-based criteria could be enabled to automatically recognize unusual patterns uncharacteristic of the norm and inform watch-standers to unsafe, illegal, threatening, and other anomalous activities. The monitoring for patterns could be used both externally and internally, allowing the commander to recognize any conditions of the system that maybe undesired.

For example, communication paths that are down or being denied and or that the system has been compromised.

c. Share Information

Now that the information has been collated, correlated, and contextualized, it can then be shared, established by its authoritative reporting responsibility, and communicated. Figure 11, depicts the Share Information function, which is essentially the key function that defines making information available for coloration with participants (people, processes, or systems) [DoD Information Sharing Executive, 2007]. Sharing information provides common mission awareness to all participants involved.

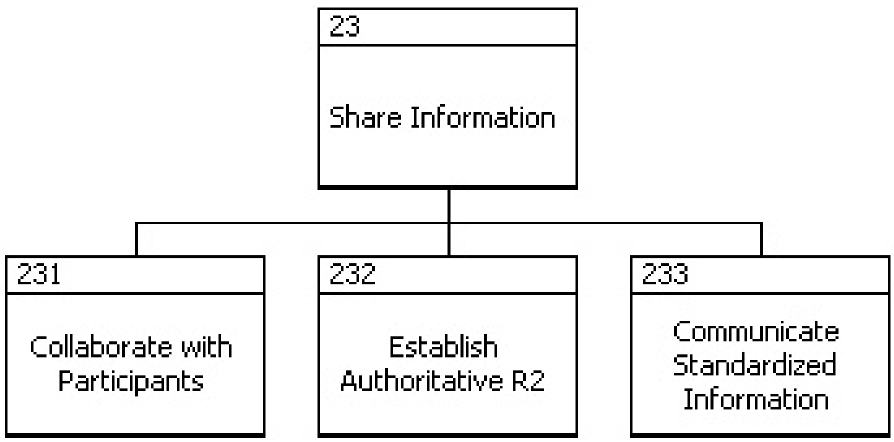

Figure 11. Share Information Functional Representation

Sharing information is the means by which participants communicate standardized information and establish a common situational awareness. Owners of the information (Authoritative R2) are required to keep the most up-to-date information for authorized participants.

The Collaborate with Participants function (A231) is the function that establishes the cooperation of forces and resources to share available information in real time. This entails providing the methods of which information can be shared, whether it is by electronic or manual systems to inform participating organizations of the mission at hand. This also entails the establishment of the trust among reporting responsibilities, agencies, organizations, and more that require the “need to know” of specific information from their respective authoritative reporting responsibility.

The Establish Authoritative Reporting Responsibility function (A232) brings together the informational flow hierarchies. In these hierarchies, standardized information needs to flow up and down the chain of command [Alberts and Hayes, 2005]. This implies that the owner of specific mission information has the responsibility to maintain and share that information as deemed appropriate. Information owners have to be intelligent with respect to knowing what information is important to what participants, and in a circuit-based communications infrastructure, they also need to be quick to know about how to reach them. This can be measured by the percent of how many participants are informed of the decision hierarchy.

The Communicate Standardized Information function (A233) is the method by which standardized information is communicated. Communication can be done by a variety of electronic sources and in many different formats

3. Plan

The planning function takes the output of Support Sensemaking function as input, and supplies the "how it should be done." Research uncovered that planning itself is not just another function of C2. It is not just a specific plan. According to the US Forces Command's, Adaptive Planning Concept of Operations, "planning includes the mutual understanding of the capabilities, limitations, and consequences of civilian and military actions and identifies ways in which military and nonmilitary capabilities best complement each other" [J9 Adaptive Planning Department, 2008].

Planning is important to the overall aspect of C2 and enables determining courses of actions (COAs), and finalizing with the promulgation. But in order to focus on decision making, further analysis will be left to future studies.

4. Command

The command function takes the planning output from the planning function and turns it into orders to be issued. This function would involve writing orders and transmitting them, as well as verifying their arrival and proper understanding by the

recipients. This function would also include monitoring the execution by means of feedback, at which the C2 process repeats itself via the frictions flow. This function is important to the overall C2 Process, but will not be dealt with any further to aid in focusing on the stakeholder issues.

To reiterate, in order to properly address and bound the problem, further discussions will only trace to the sensemaking aspects of the system.

C. FUNCTIONAL FLOW ANALYSIS

Enhanced Functional Flow Block Diagrams (EFFBDs) have been used to show the functions and their order that the Common C2 needs to perform. EFFBD also displays the controls and the data flow. This functional analysis has been chosen to not only show the dynamics of the system, but to also allow for easier modeling of the data dependencies. The model developed using EFFBD will serve as the functional architecture for the Common C2, and it also helped examine each of the its functions and sub-functions. An EFFBD model for the Common C2 system has been developed using CORE. CORE is a systems engineering tool developed by Vitech Corporation and aides in requirements management, functional analysis, architecture development, and verification and validation.

1. C2UniArch Functional Flow

a. A0 Provide Common C2 Functional Flow

The Common C2 system has been decomposed into following four functions which are: Collect Information, Support Sensemaking, Plan, and Command. Figure 12 shows the top level EFFBD for Common C2. This serves as the first layer of functional flow for the Common C2.

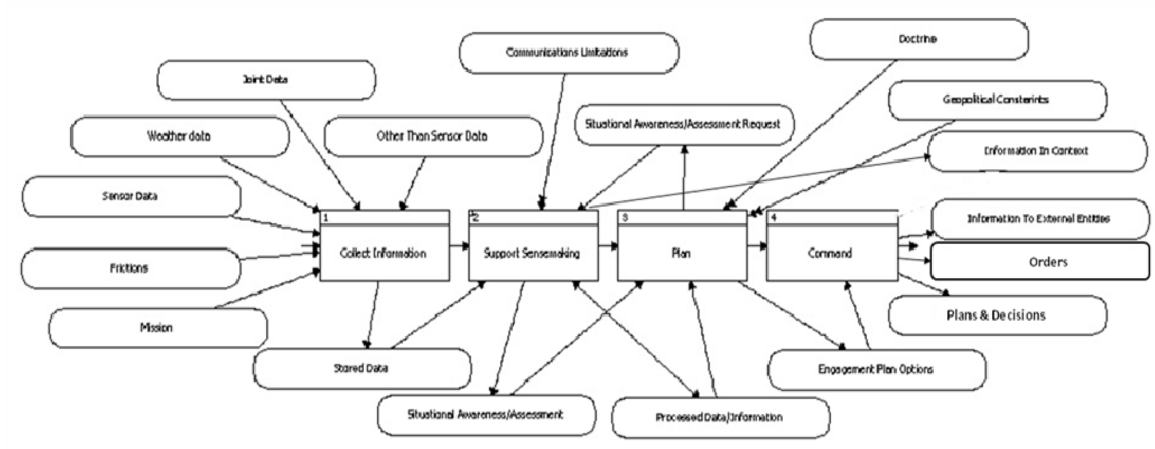

Figure 12. Provide Common C2 EFFBD

The top level functions and their order of relationships with each other are essential in providing the necessary means to perform C2. The collection of information and making sense of it is crucial for the planning and the execution of decisions.

EFFBD in Figure 12 demonstrates the sequential order of all the major functions of the Common C2. Each of the functions is triggered by the one preceding it. The Collect Information function fulfills the data collection and dissemination requirements. The data from Collect Information function is passed to the Support Sensemaking function. The Support Sensemaking function uses this data and puts it into perspective by producing understanding of the situation, and determining what needs to be done to accomplish the mission. The Plan function takes the output of the Support Sensemaking function and determines how the mission needs to be accomplished. Finally, the Command function is the final piece of the Common C2 system. It takes the output of the Plan function and provides the final authority for execution of the plan.

Because of the narrowed scope this project, only Support Sensemaking function functional flow has been analyzed in more detail. Figure 13 depicts the IDEF0 for Support Sensemaking function. This is the second layer of decomposition for the Common C2 architecture.

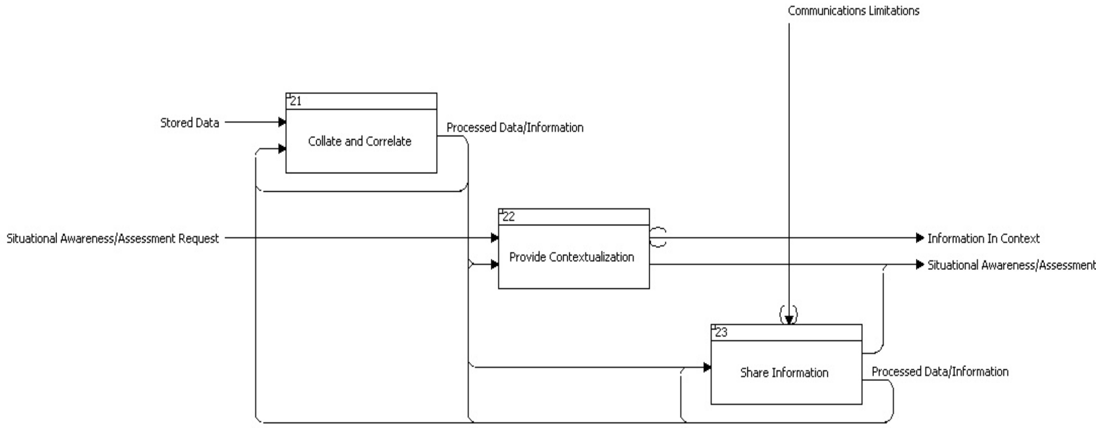

Figure 13. Support Sensemaking IDEF0

The functional flow of the Support Sensemaking function consists of Collate and Correlate, Provide Contextualization, and Share Information sub functions. This IDEF0 demonstrates the sequential nature of functions required to provide Support Sensemaking capability for the Common C2.

Support Sensemaking function consists of three functions which are: Collate and Correlate, Provide Contextualization, and Share Information. The Collate and Correlate function creates associations between related data. The Provide Contextualization function provides context to the data or event. The Share Information function provides collaboration, report and responsibility, and communication capability.

b. A21 Collate and Correlate Functional Flow

To further understand the sub functions of the Support Sensemaking function, the third layer of functional analysis for the Common C2 architecture was analyzed. The third layer of functional analysis shows the functional flow of Collate and Correlate, Provide Contextualization, and Share Information functions. The first function from this decomposition is the Collate and Correlate function. Figure 14 depicts the EFFBD for the Collate and Correlate function.

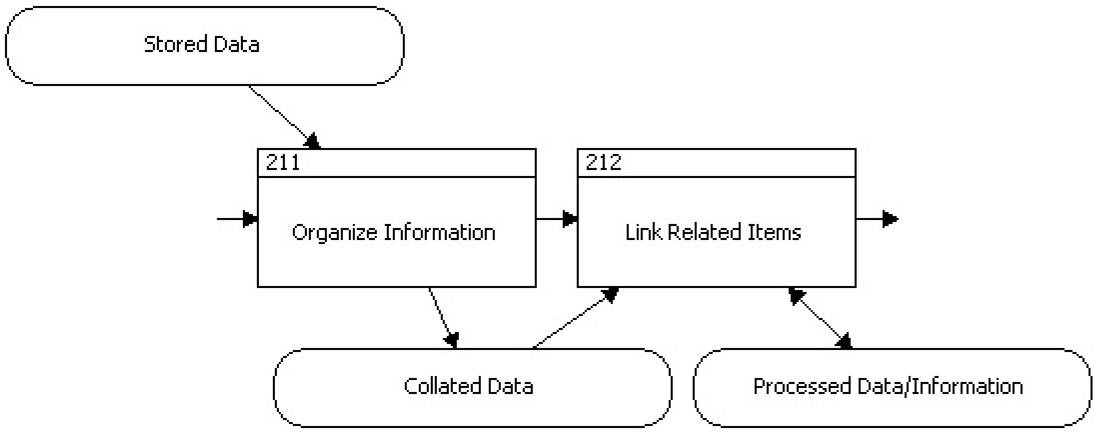

Figure 14. Collate and Correlate EFFBD

The Collate and Correlate function consists of Organize Information, and Link Related Items sub functions. The Organize Information sub function is essential to collate data and information. The Link Related Items sub function is essential to make associations between data and information.

The functional flow of Collate and Correlate function shows that the ambiguity among the data is reduced, information is organized, associations are created, and links are created among similar data and events.

c. A22 Provide Contextualization Functional Flow

The next function in the third level of functional analysis is the Provide Contextualization function. Figure 15 shows the EFFBD for this function. The functional flow of Provide Contextualization function is unique because it demonstrates the concurrency in execution of Establish Knowledge of Battlespace, Alert on Pattern Anomaly, and Provide Common Visualization sub functions. The combined output of all these sub functions is what is passed out to the Share Information function.

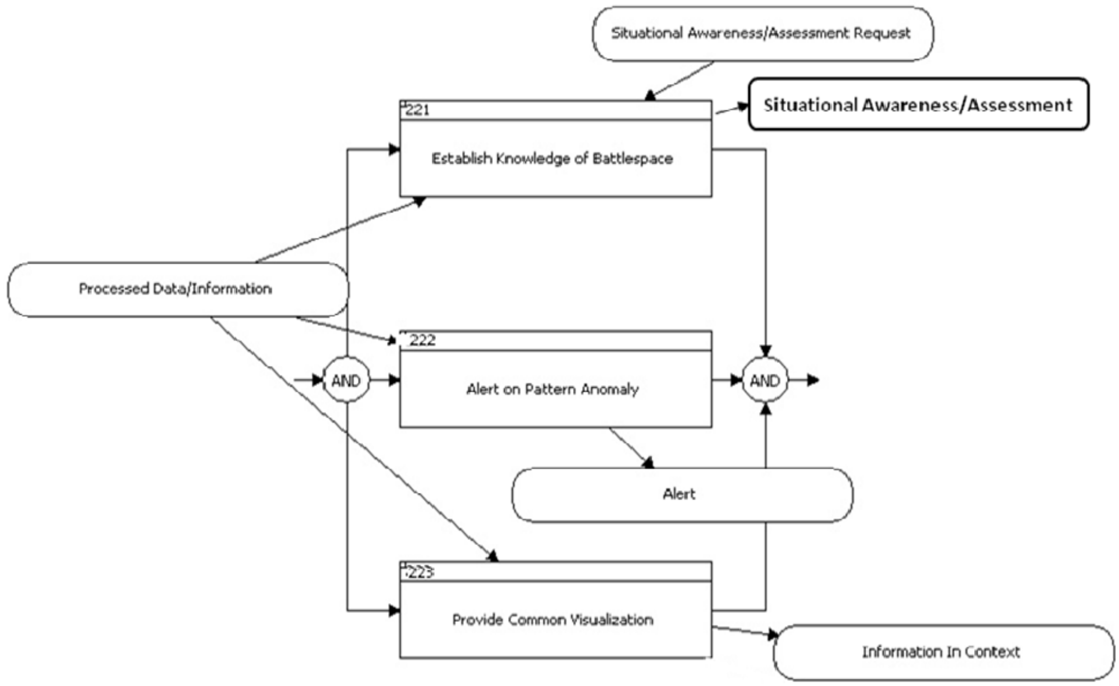

Figure 15. Provide Contextualization EFFBD

The Provide Contextualization function consists of Establish Knowledge of Battlespace, Alert on Pattern Anomaly, and Provide Common Visualization sub functions. This EFFBD demonstrates the concurrency of these functions and that all of the pieces are necessary to share information. In the higher level EFFBD Alert is considered a part of the Situational Awareness/Assessment output.

The EFFBD for Provide Contextualization function demonstrates the concurrency of the sub functions. Establish Knowledge of Battlespace, Alert on Pattern Anomaly, and Provide Common Visualization all occur in parallel. Because this paper is investigating the visualization aspect of Common C2, each of these sub functions will need to be decomposed for further analysis and understanding. This will result in the fourth layer of decomposition. Establish Knowledge of Battlespace, Alert on Pattern Anomaly, and Provide Common Visualization functions functional flow is shown in Figures 16, 17, and 18 respectively.

Alert on Pattern Anomaly generates the output Alert. Alert is shown in Figure 15 to provide traceability to the lower level EFFBDs. However, it has been omitted from the

higher level EFFBDs because Alert is considered a part of the Situational Awareness/Assessment output.

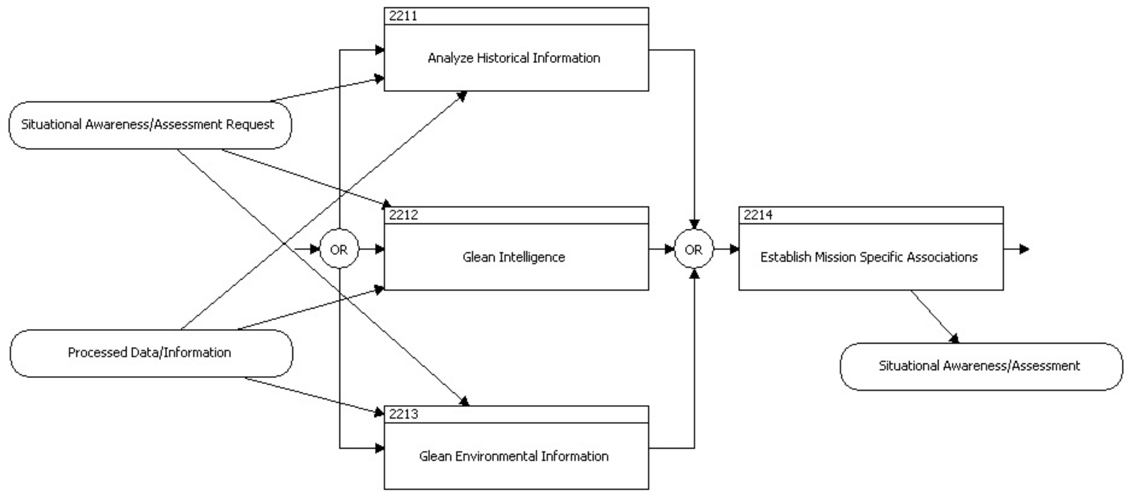

Figure 16. Establish Knowledge of Battlespace EFFBD

The Provide Knowledge of Battlespace function consists of Analyze Historical Information, Glean Intelligence, Glean Environmental Information, and Establish Mission Specific Associations. All of these sub functions are necessary to analyze the situation with respect to the surroundings and establish a perspective.

The Establish Knowledge of Battlespace function uses the historical, intelligence, and environmental data to establish perspective. This function consists of Analyze Historical Information, Glean Intelligence, Glean Environmental Information, and Establish Mission Specific Associations sub functions. As shown the functional flow in Figure 16, Analyze Historical Information, Glean Intelligence, and Glean Environmental Information functions have a parallel relationship and are in series with Establish Mission Specific Associations function. The parallel and series relationship can be explained by the fact that historical, intelligence, and environmental information are needed prior to creation of associations.

Alert on Pattern Anomaly, contained in the fourth layer of functional analysis, is presented in Figure 17.

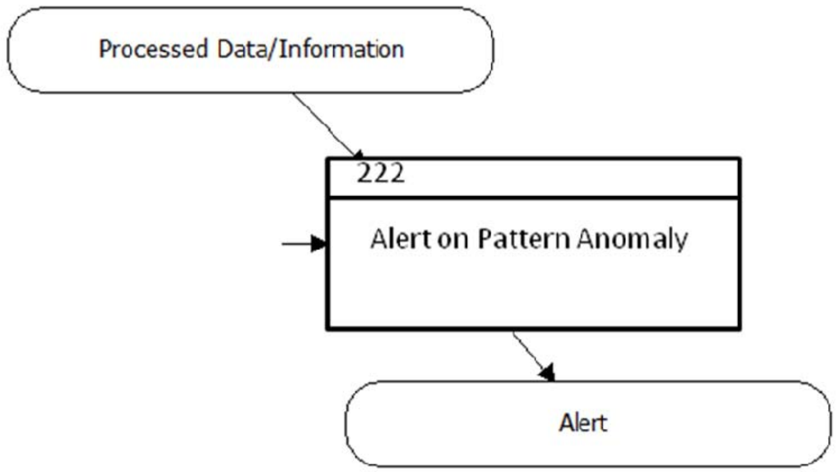

Figure 17. Alert on Pattern Anomaly EFFBD

The Alert on Pattern Anomaly function consists of one output Alert. For the Common C2 system, it is essential to keep track of changes as it relates to data and information; therefore, generating alerts when there is an anomaly is essential.

Alert on Pattern Anomaly function generates an Alert output. This function enables the system to stay updated as changes are detected. These changes could be a result of new alerts as they become available or existing alerts that are not relevant anymore.

The Provide Common Visualization function, contained in the fourth layer of functional analysis, is presented in Figure 18.

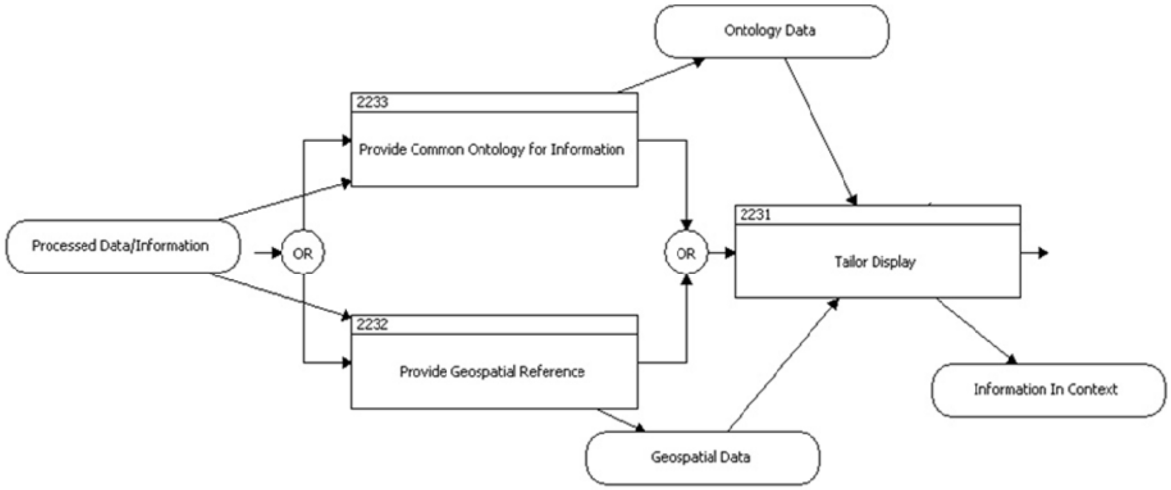

Figure 18. Provide Common Visualization EFFBD

The Provide Common Visualization function consists of Provide Common Ontology for Information, Provide Geospatial Reference, and Tailor Display sub functions. Common ontology for information and accurate geospatial reference are essential for the Common C2 system to effectively provide a standardized tailored display to the operators or decision makers.

The Provide Common Visualization consists of the Provide Common Ontology for Information, Provide Geospatial Reference, and Tailor Display sub functions. It provides common ontology for information and geospatial reference. Its final output is a tailored display. This sub function concludes the Provide Contextualization function.

d. A23 Share Information Functional Flow

Going back to the third layer of functional analysis, Share Information function is the next function following the Provide Contextualization function. It is the third sub function under the Support Sensemaking functional hierarchy. Figure 19 presents the EFFBD for the Share Information function.

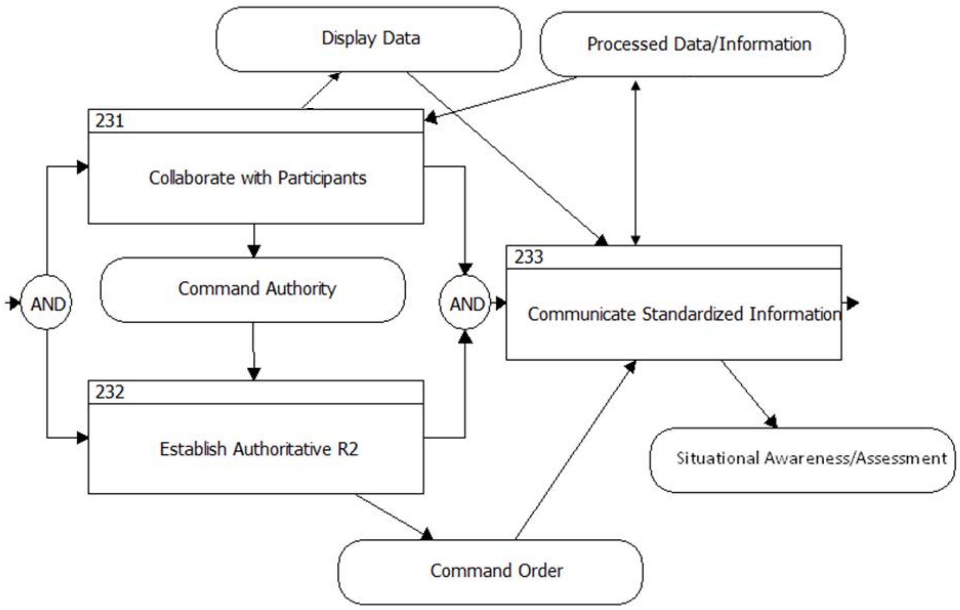

Figure 19. Share Information EFFBD

The Share Information function consists of Collaborate with Participants, and Establish Authoritative R2, and Communicate Standardized Information sub functions. This function will enable the Common C2 system to effectively share information for all concerned groups.

The Share Information function consists of Collaborate with Participants, Establish Authoritative Reporting and Responsibility (R2), and Communicate Standardized Information sub functions. This function is responsible for establishing reporting and responsibility authority and communication of the information. As shown the functional flow in Figure 19, Collaborate with Participants and Establish Authoritative R2 functions have a parallel relationship and are in series with Communicate Standardized Information function. The parallel and series relationship can be explained by the fact that collaboration, and reporting and responsibility tasks are needed prior to communication of the information in a standard format.

2. Non-Functional Decomposition

Upon decomposition of the functions and discussion with the stakeholders with regard to objectives, the team was able to capture desired attributes and characteristics of the target architecture. Functional analysis aided in identifying related objective

interactions among relevant elements of the problem and was categorized as non-functional requirements.

The following are explanations utilized to aid in defining those characteristics. Figure 20 is a hierarchical depiction of the criteria that can be used to judge the operation of the architecture.

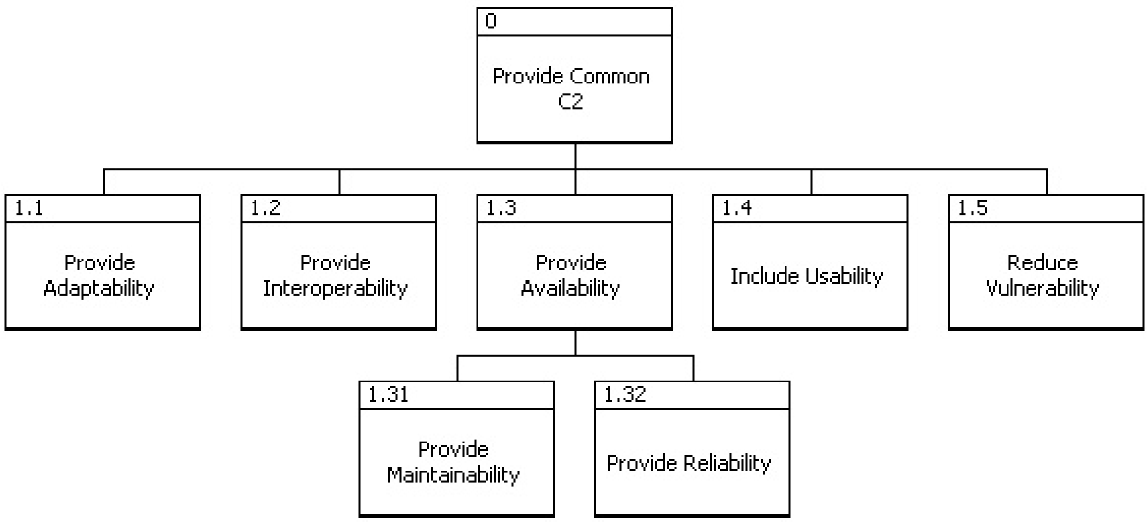

Figure 20. Provide C2 Functional Decomposition

These non-functional requirements were decided from the stakeholder's analysis as being the quality attributes desired of the C2 system.

a. Provide Adaptability

Provide adaptability was derived from the stakeholders' need for a system that is highly adaptable for future upgrades. There is also a need to ensure that a C2 system can support interface changes without major impacts to the supporting the mission threads. Adaptability for this instance can be defined as the ability to change to fit new or special external or internal interfaces. Adaptability will be measure by compliance with agreed upon DoD recognized open or military standards.

b. Provide Interoperability

Interoperability: The ability of systems, units, or forces to provide data, information, materiel, and services to and accept the same from other systems, units, or forces and to use the data, information, materiel, and services so exchanged to enable them to operate effectively together. National Security System (NSS) and Information Technology System (ITS) interoperability includes both the technical exchange of information and the end-to-end operational effectiveness of that exchanged information as required for mission accomplishment [JCS 1-02].

Provide Interoperability is a common DoD requirement and is derived from the requirement to cooperate and communicate between systems and platforms. Interoperability is defined above and is a measure of how much context and semantic continuity is maintained by the systems use of interfaces to other systems and the user graphical interface. The system is required to comply with DoDD 4630.5 and DoDI 5000.2 interoperability guidance.

c. Provide Availability

Operational Availability (A_O): The degree (expressed as a decimal between 0 and 1, or the percentage equivalent) to which one can expect a piece of equipment or weapon system to work properly when it is required, that is, the percent of time the equipment or weapon system is available for use. A_O represents system "uptime" and considers the effect of reliability, maintainability, and mean logistics delay time. A_O may be calculated by dividing Uptime by Total time. UP time is the time a system is operational between failures. DOWN time is the time the system is not operational that is, A_O = System Up Time / Total Time (Up Time + Down Time). It is the quantitative link between readiness objectives and supportability [CJCSI 3170.01F].

Provide Availability is important to the user because the measure of system effectiveness relates directly to the system hardware, software, support, and environment characteristics, which include Operational Availability (A_O) and Mean Time Between

Failure (MTBF) into one significant parameter. Through research of like systems and stakeholder interviews it was determined the system needed to maintain an A_O of .98.

d. Provide Reliability

Provide Reliability was determined as the need to reduce the likelihood of failure. As per discussions with stakeholder the desired reliability of the system and availability will have the appropriate MTBF of no worse than the as-is state.

e. Include Usability

Include Usability is a supportability need the stakeholders' expressed to ensure integration of requirements for the human into the system. Usability is defined as ease with which people can employ a particular functional aspect of the system and the ease of operation. System objectives as confirmed by the Surface Warfare Program Manager's Guide and the stakeholders are [Malone, 2001]:

- Reduce the incidence and impact of human errors (the direct cause of 80% of ship accidents)
- Enhance human performance, specifically situational awareness and decision making
- Improve training and personnel management which can be measured by change in training time required

f. Reduce Vulnerability

Vulnerability is the need to protect and defend information or weaknesses present in the architecture. Reduce vulnerability is the requirement of ensuring the system is able to be configured to meet and maintain minimum Information Assurance (IA) Defense in depth standards, to include certification and accreditation IAW the DoD Information Technology Security Certification and Accreditation Process (DIACAP) [DoDI 5200.40]. The system is required to comply with a security posture IAW DoDD 8500.2 at a MAC level I.

D. PRELIMINARY REQUIREMENTS

Stakeholders were involved in developing requirements and building an understanding of the problem. Elicitation resulted in the analysis of the system objectives and functional analysis. The summary of requirements in Table 3 trace from stakeholder desired system objectives to the system functions. To focus on the stakeholder problems, two areas were addressed: overall system objectives and requirements related to creating understanding, or sensemaking. The latter produced requirements resulting from decomposition of C2 and proper sensemaking vice explicitly stated stakeholder needs. These top level requirements were also essential for specifically addressing C2 architecture problems.

Once system functions were understood, the team was able to articulate the system specifications into clearly stated language. The following requirements are preliminary and have not been validated through formal DoD Joint Capabilities Integration and Development System (JCIDS) or Naval Net Warfare Command (NNWC) review.

Unfortunately, many of the interface methods used by existing C2 sensemaking systems do not necessarily have good time-constrained behavior. There is also the recognition that data arrives from differing sources at various rates. Due to the large variations in data arrival rate times, data retrieval and sensemaking functions were not constrained to a specific time and will be needed as quickly as possible.

REF	Function	Requirement
A0	System Level	System interface should be intuitive and system should reduce operation complexity by complying with MIL-STD-1472F
A1.1	Collect Information	Maintain situational awareness state in a disconnected or electronically denied environment for a minimum of 24hrs
A2.1	Provide Sensemaking	The systems shall reduce uncertainty by reducing ambiguity. All objects or tracks in the system shall be maintained and ambiguity reduced to less than 1%
A2.2	Provide Sensemaking	The system shall provide for reduced reaction time by providing in-context, concise information presentations, and reduce average decision time, no worse than current systems, by timely presentation of mission-relevant and mission-critical information
A2.3	Provide Sensemaking	The systems shall increase quality of information produced by ensuring data is complete. System shall increase average number of Friendly, Hostile, Neutral and Non-Military correctly identified over aggregated time.
A223	Provide Common Visualization	Design and arrangement of displays and controls shall be consistent with the operator's and maintainer's tasks and actions
A2232	Provide Geospatial Reference	The system shall be capable of representing the physical domain supporting existing geospatial formats. Requirements for Geospatial Information and Services shall meet CJCSI 3901.01B
A212	Link Related Items	System shall establish relationships among objects in terms of their identification, deployment, kinetic interaction, organization role, and type similarity with 99.9% accuracy
A212	Link Related Items	Establish relationships between sensors and sensed entities as well as relationships between entities of interest and other entities with 99% accuracy
A212	Link Related Items	Conceptual categorization and organization of data shall be made explicit to the operator for rapid detection and classification of a situation
A22	Provide Contextualization	The system shall provide the ability to view the past, present and predicted situation to include location, identity, status and intentions of Friendly, Hostile, Neutral and Non-Military entities historically, currently or planned. The user shall be able to view a prediction of the current situation into the future based on background knowledge about the dynamic of situation contingencies
A221	Establish Knowledge of Battlespace	The system shall account for existence of elements of the situation and allow access to display elements to include intelligence relevant to mission, environmental information, and historical information.

A223	Provide Common Visualization	The system shall provide a flexible and adaptable mode of visualization and interaction that is independent of the data infrastructure.
A2231	Tailor Display	The system shall be able to tailor display based upon user set criteria and support for user-driven selection of information sources
A2233	Provide Standard Ontology for Information	The system shall make use of effective and consistent labels, symbols, colors, terms, acronyms, abbreviations, formats, and data fields by following MIL STD 2525Bc1
A2222	Alert on Pattern Anomaly	The system shall provide an indication via visual and audio (configurable) alert when elements do not match because values of a parameter are different, an event occurs that should not, or an event does not occur that was registered.
A233	Communicate Standardized Information	The system shall provide shared situational awareness by minimizing average time to disseminate information (less than 1 second from transmission)

Table 3. System Functions and Requirements

This table lists the system functions for the major sensemaking functional objectives and their respective requirements.

E. VALUE SYSTEM DESIGN

Once the system functions were developed and the requirements were understood and verified by stakeholders, the team utilized these to guide in defining measurable system performance. The need to improve Sensemaking to be more efficient and effective requires an examination of the overall C2 Architecture. This is not an exercise to re-design C2 but to evaluate the architecture, looking for ways to improve the decision making process. Value System Design (VSD) is used to identify the objectives, measures, and desired values to establish criteria, which will be used to determine how well a potential alternative may be evaluated to improve Sensemaking. This is done by decomposing the C2 functions into objectives and evaluation measures.

1. Value System Modeling

The Value System Model was developed as a qualitative method to organize the stakeholders' functional objectives. This model provides a method to transform the stakeholders' functional objectives into functional requirements. To measure how

effective the functional requirements are, quantitative measures are needed to determine if the C2 systems meet these requirements. These are captured as evaluation measures. Figure 21 represents the process model taking the stakeholders' functional objectives and converting them to a well-defined requirement. Then criteria are determined to measure effectiveness and performance.

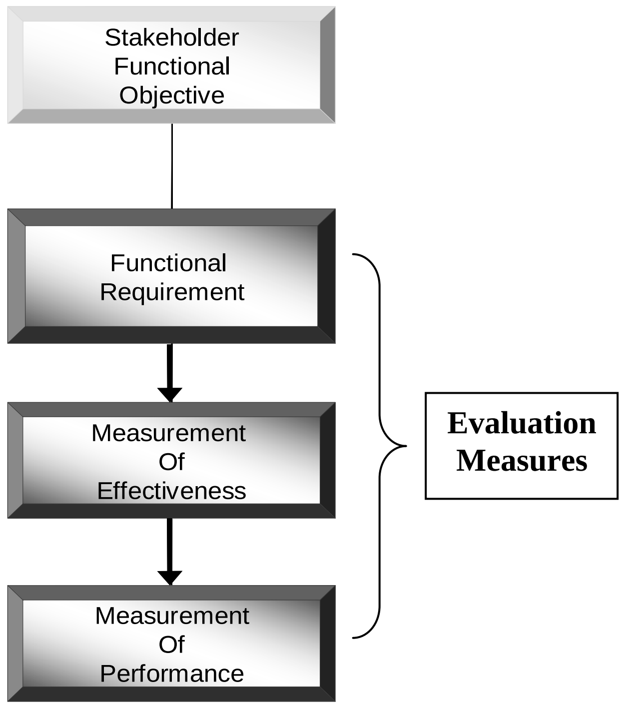

Figure 21. Value System Process Model

This process model illustrates the progression from the Stakeholders Functional Objectives transformation to quantifiable evaluation measures. These evaluation measures will aid in determining how well the system is doing, and if the system is meeting stakeholder goals.

2. Value Hierarchy

The top-level Value Hierarchy for Support Sensemaking is shown in Figure 22. These functions are an aggregation of the resource sponsor inputs from interview and questionnaires. Once the stakeholders' analysis was conducted the need to decompose Support Sensemaking was clear.

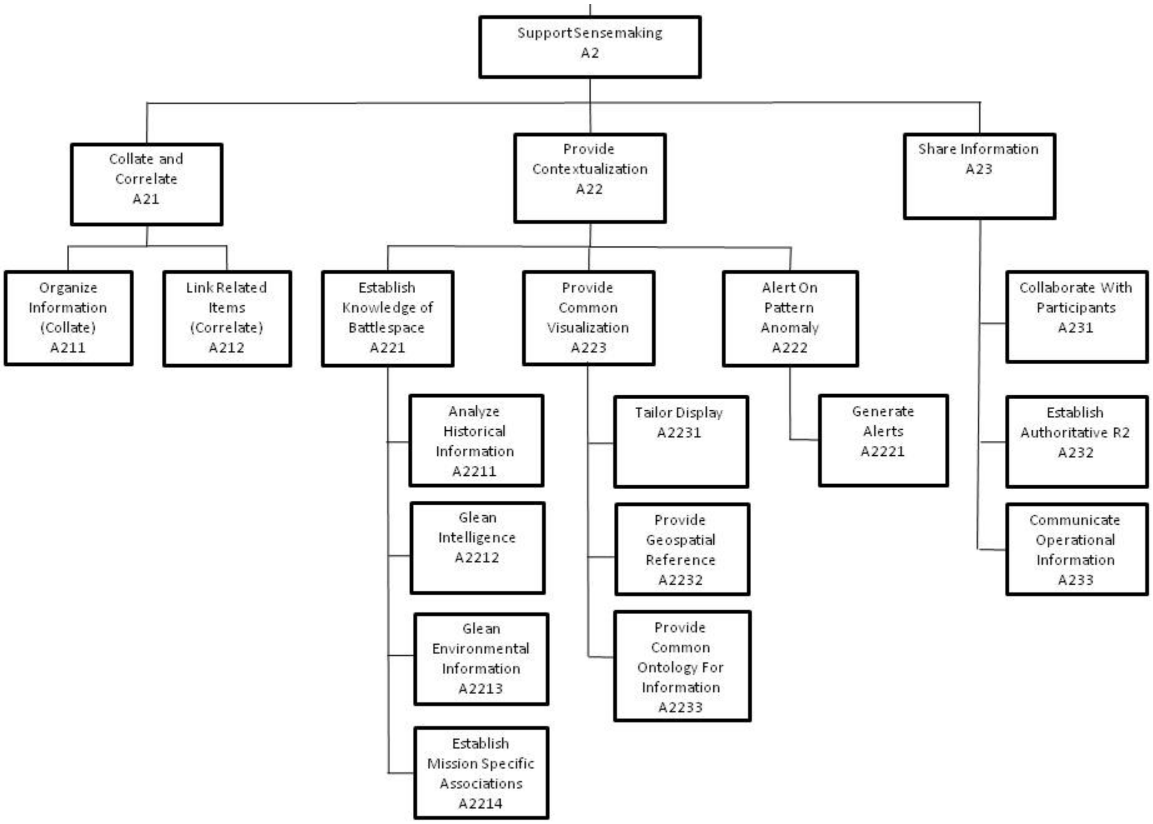

Figure 22. Support Sensemaking

The Value Hierarchy of Support Sensemaking showing system functions is illustrated in this figure. It sets an order of importance of the sub-functions of Support Sensemaking into Collate and Correlate, Provide Contextualization, and Share information.

3. Evaluation Measures

Sensemaking has two objectives; the first is to reduce uncertainty and is measured by the probability of decision error (the lower the better). This objective captures how the system is reducing the amount of questionable data the users have to evaluate. Does the decision maker have all the required data they need to make a decision? The second objective is to decrease reaction time which is measured by the elapsed time from first receiving the data to making a decision (the lower the better). This objective captures how long it takes a decision maker to make a choice once the system has provided all requested data.

A sub-function for Support Sensemaking is Provide Contextualization. This sub-function was targeted because of the objective to increase the quality of information

produced. This objective ties into the Support Sensemaking objective to reduce uncertainty by its evaluation measure information accuracy and completeness. The higher the ratio the better the quality of the decision made.

Although not a part of Supporting Sensemaking function, training is another benefit as a part of this reports decision making analysis. The training function has two objectives, the first is decrease training hours and is measured by change in training time required (less is better). It is the position of this paper that with commonality particularly in the common visualization component would provide opportunities for cost savings in the way of reduced training time. One way to verify that a decrease in training hours has occurred is to measure the time required to train an alternative system versus the as-is system. The second objective for training is training efficiencies which is measured by change in training cost (lower is better). Training cost can be related or tied to the amount of hours trained. So if the amount of hours decrease from the as-is system due to efficiencies provided by the alternative system, training cost will tend to decrease as a result. Table 4 shows the key evaluation measures, their objectives, and associated C2 functions. A more complete list of evaluation measures for Support Sensemaking is in Appendix D of this report.

REF	Function	Objective	Evaluation Measure
A2.1	Sensemaking	Reduce uncertainty	Number of failures in making a decision within an allotted time and number of total decisions. (less is better)
A2.2	Sensemaking	Decrease reaction time	Average elapsed time for decision. (less is better)
A2.3	Sensemaking	Increase quality of information produced	Average number of data elements that enhance the decision above what is required. (less is better)
A21.1	Collate	Increase situational awareness	Percentage of accurately identifying critical elements properly. (greater is better)
A213.1	Correlate	Increase information clarity	Number of data elements in unambiguous state. (lower is better)
A22.1	Contextualization	Increase quality of information produced	Information accuracy and completeness. (more is better)
A222.1	Common Visualization	Improve geospatial Information	Maximize geospatial accuracy (mean of positional accuracy). (less is better)
A223.1	Standard Ontology	Decrease Training and reaction time by maximizing use of standards	Compliance of information displayed using proper standard:(MIL STD 2525Bc1). (less is better)
A23.1	Share	Improve Timeliness of information	Minimize Average Time to disseminate. (less is better)
	Training	Decrease training overlap and redundancy	Change in training time required. (less is better)

Table 4. Key Evaluation Measures

The key (highlighted) evaluation measures were the focus of evaluation the C2 As-Is system along with the alternatives.

The Introduction and Problem Definition section addressed the primary question, “what are the functions of C2 at the surface combatant level?” These sections identified the main C2 functions as Collect Information, Support Sensemaking, Plan, and Command. The Support Sensemaking function was the focus of this paper and was decomposed into Collate and Correlate, Provide Contextualization, and Share Information sub-functions. Each sub-function was decomposed additional levels as necessary until the respective sub-function objective addressed a requirement, or partial requirement, and suitable measures of effectiveness were established.

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III. DESIGN & ANALYSIS

A. ALTERNATIVES GENERATION

The first step of the alternatives generation process included brainstorming for technology and existing systems that satisfied, or could be modified to satisfy the Support Sensemaking's functions and requirements. Support Sensemaking is made up of the functions Collate and Correlate, Provide Contextualization, and Share Information. The second step was to build on the brainstorming results and fit potential solutions together as alternatives, ensuring the defined sub-functions were all satisfied by each alternative. This yielded four complete alternatives to be further analyzed.

For the final step, four alternatives were analyzed in a feasibility screening. Two were selected for a more detailed comparison against the As-Is architecture. A detailed description of the remaining alternatives is provided later in this report. The descriptions below show how these alternatives' functions support a common visualization methodology, which presents all available C2 data in a well-organized and uniform way.

1. Development of Alternatives

Uncertainty can cause delays in decision making with respect to Command and Control. The goal is to make the decision making aspect of C2 faster, increase decision quality, and decrease decision error. In order to improve sensemaking and facilitate decision making, the Support Sensemaking functions have been analyzed.

The functional analysis and decomposition of the Support Sensemaking function produced Collate and Correlate, Provide Contextualization, and Share Information sub functions. These primary functions were carried forward into the Zwicky's Morphological process. In this process, several brainstorming exercises produced alternatives that satisfy and achieve the results that these sub functions were intended to achieve. In addition, how Support Sensemaking's primary functions could be executed was researched via the web, interviewing stakeholders, and examining how similar functions are performed in other systems. Some examples of sources consulted are

Defense Technical Information Center (DTIC), research performed on Berndt Brehmer's works, news websites, and various DoD publications. Shifts in DoD design philosophies were also considered, for example, the desire for Service Oriented Architectures (SOAs).

Following the brainstorming exercises and research, these alternatives were organized in the Zwicky's Morphological Box which is shown in Appendix B. From the Zwicky's Morphological Box, the alternatives for each of the sub functions were combined to form new architecture alternatives. The only architecture alternatives that were considered for further study and analysis are displayed in Table 5. Other architecture alternatives that did not appear to be feasible were discarded.

Alternatives – Support Sensemaking			
Alternative Name	**Collate and Correlate**	**Provide Contextualization**	**Share Information**
The Hybrid	Unique Interface Correlation Server (UICS)	Mixed Legacy (ADS) and New Standardized and Customizable Visualization	Use of Legacy (TADIL or CEC) and New Real-time Data Distribution Service
Global Understanding Network (GUN)	Service Adapter	New Standardized and Customizable Visualization	Real-time Data Distribution Service
3-D Display	Common Computing Correlates	Three Dimensional Display only (e.g., Google Earth)	Use of Legacy (TADIL or CEC)
Holographic Walkthrough Environment	Quantum Computing	Holographic Imaging	Updated to share new data

Table 5. Alternatives Table

Results from the alternative generation provided four alternatives that support sensemaking. The As-Is provides the baseline for the newer alternatives.

Table 5 shows how Support Sensemaking's functions have been addressed by the candidate architectures. A brief description of alternative architectures is presented next. Each description includes how the alternative addresses Support Sensemaking's functions.

2. Brief Alternatives Description

Hybrid architecture alternative – This architecture modifies the As-Is architecture's Collate and Correlate and Provide Contextualization functions. The Hybrid architecture introduces a Unique Interface Correlation Server (UICS), which takes the data and information from all of the processing systems of the As-Is architecture for the Collate and Correlate function. The Hybrid architecture performs the Provide Contextualization function through a single, user-customizable display, where all of the available mission critical information is made available to the user and decision maker.

GUN architecture alternative – This architecture differs from the Hybrid architecture's Collate and Correlate, Provide Contextualization, and Share Information functions, however, there are many similarities between the Hybrid and GUN architectures. The GUN utilizes service adapters that take all the data and information from the processing systems and converts them into universal formats. The converted data is then used to perform the Collate and Correlate function. After correlation checks are complete, the data is available to the users and decision makers. The users and decision makers can tailor this information for their specific requirement on a single display, thus performing the Provide Contextualization function. The Share Information function is performed by a real-time data distribution service which allows the information to be shared with remote allies.

3-Dimensional Display alternative - For the Collate and Correlate function a Common Computing Correlator would be used similar to the Hybrid alternative's UICS. Similar to the GUN, a single customizable display would be used in order to Provide Contextualization. This display would be a 3-Dimensional holographic display to enhance the visualization of the operational picture [AIST, 2006]. This allows the user to

see the operational picture from all angles. This alternative makes use of currently available technology to perform the Share Information function.

Holographic Walkthrough Environment alternative - Quantum computing brings together information using information theory, computer science, and quantum physics [Steane, A, 1998]. This encompasses using specific theorems, error correcting codes, correlations, key distributions, quantum algorithms and more to treat information in a variety of ways. This allows information to process much more quickly in support of collation, correlation, a holographic environment, and information sharing. The Holographic Walkthrough Environment is an enclosed room in which objects and people are projected by a holographic display system; this audio-visual platform adds the ability to support real-time collaborative and 3-D interaction between geographically distributed war fighters. This enhances both the Provide Contextualization and Share Information functions.

In the next step of the system engineering process, a feasibility screening was conducted in order to determine which alternatives were best suited to continue with further evaluation.

B. FEASIBILITY SCREENING

Four criteria were selected for a feasibility screening. The criteria are Technological, Physical, Operational, and Financial. Each of the alternatives has been evaluated against the criteria. The alternatives that have failed to meet the criteria have been considered a “no go” and have been eliminated from further analysis. The two alternatives that have been selected for further analysis are the Hybrid and GUN.

1. Criteria Selection

The following criteria were selected to evaluate the proposed alternatives. A detailed description of each criterion is given below along with what will cause an alternative to be deemed a failure in that category.

Technical Feasibility: To receive a passing grade, there is an expectation that this alternative will be available in a reasonable time-frame. The alternative will receive a failing grade if the technology, while feasible, will not be available in ten years. Ten years were chosen as being a reasonable time-frame at the current pace of technology evolution unless there is an unforeseen breakthrough that dramatically reduces the time to move from a laboratory into a production environment.

Operational Feasibility: To receive a passing grade the alternative is expected to reduce uncertainty and provide a richer straight forward operational picture. If it is not likely that the alternative will create a better operational picture and thereby reduce decision uncertainty, it will receive a failing grade.

Physical and Environmental Feasibility: To receive a passing grade, the alternative is expected to function normally in the intended surroundings. If the alternative is not likely to function normally in the intended surroundings, then a failing grade is assigned. Because this system is expected to operate on a ship, attention must be paid to SWaP (size, weight, and power requirements). Extraordinarily large systems may weigh too much, consume too much power or have cooling requirements that could be unattainable within the confines of the allotted spaces. The system must also be able to pass shock and vibration requirements.

Cost Feasibility: To receive a passing grade, the alternative costs are expected to be in-line with other programs of equal complexity. This includes any large expenditure for new technology development. If the alternative costs are expected to be significantly larger than similarly complex programs, a failing grade will be assigned. An alternative must cost no more than twice the cost of refreshing the As-Is architecture. In the next section, each of the alternatives has been judged by these criteria. Those that failed in

any one of these categories have been eliminated as a possible alternative. Those that have passed the screening moved to alternative scoring and cost analysis.

2. Screening

Each of the proposed alternatives has been evaluated against the selected criteria. A simple pass or fail was given to each alternative. Table 6 displays the results.

Requirements and Constraint	Alternatives			
	Hybrid	**GUN**	**3DD**	**Holographic Walkthrough Environment**
Technical	**Pass**	**Pass**	**Fail**	**Fail**
Physical and Environmental	**Pass**	**Pass**	**Pass**	**Fail**
Operational	**Pass**	**Pass**	**Pass**	**Pass**
Cost	**Pass**	**Pass**	**Fail**	**Fail**
RECAP	**Pass**	**Pass**	**Fail**	**Fail**

Table 6. Feasibility Screening

Each alternative was evaluated against the specified criteria for feasibility. A fail was given to the alternatives that did not pass all of the criteria.

The Holographic Walkthrough Environment alternative failed the feasibility screening. It is technologically infeasible at this point. Development costs would be excessive in an attempt to create a workable holographic walkthrough; it has also failed in the Cost category. It has also failed in the Environmental category because the ships being considered have a very limited amount of space. The idea of the Holographic Walkthrough is to provide a large room which you can walk though and interact with the items displayed. It is simply too large to be put on the platforms being considered.

The 3DD has also failed. It has failed in the Costs and Technical categories. Although preliminary development has begun on such a display, unless there is a technology breakthrough, a substantial development investment must be made before the

technology is ready to depict the operational environment at the necessary level of detail. The technology currently does not address any particular operational requirement.

Both the Hybrid system and the Global Understanding Network system have passed and will be examined in the next section. Both these alternatives meet the fundamental functions of sensemaking, however what makes them different is how they fulfill the functions. A detailed description of these systems along with the As-Is is explained in the next section.

C. DETAILED ALTERNATIVES DESCRIPTION

1. As-Is Description

On the typical naval surface combatant platform, in this case the Ticonderoga class cruiser and Arleigh Burke class destroyer, the CIC includes multiple C2 systems that accomplish the Collate and Correlate, Provide Contextualization, and Share Information functions. The typical location of the C2 display systems in the CIC are depicted in Figure 23. The various systems are represented by shading and mapped to its typical location. The asterisk marks future C2 display systems that are slated to be added to the CIC.

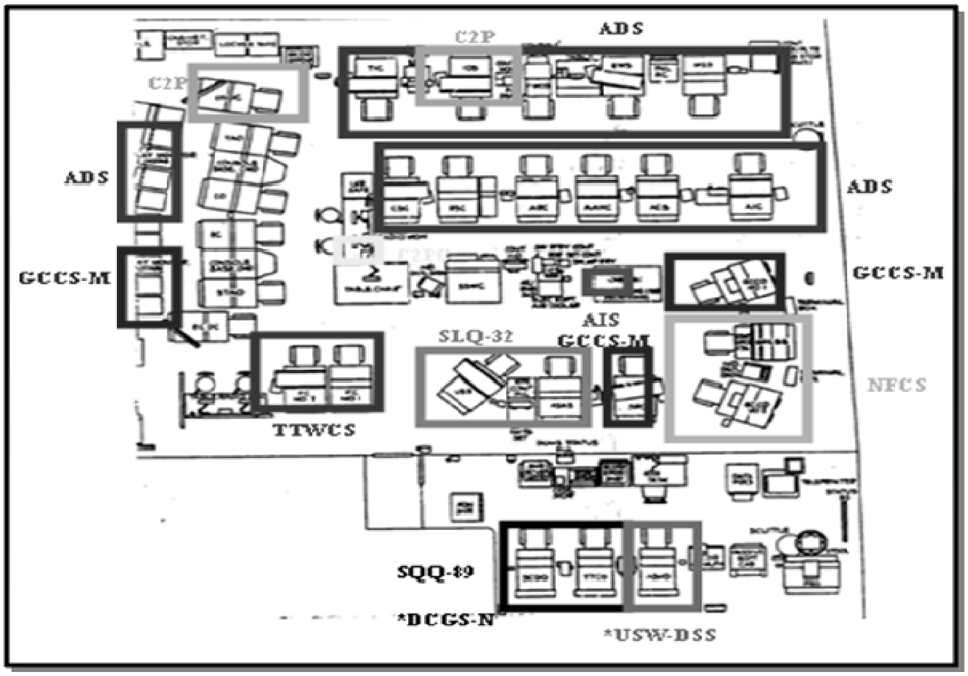


Figure 23. Typical Display Consoles in CIC

This is a layout of the combat information center aboard a typical Ticonderoga class cruiser. C2 systems and components, which are used in the CIC, are identified including future systems that will soon be added. [Picture from Military.com]

The systems comprising the current As-Is architecture perform some of the same functions. For example, the Tactical Tomahawk Weapon Control System (TTWCS) is a system that collects and correlates information, provides a visual display, and shares information. A second system that can accomplish these functions is the Naval Fires Control System (NFCS) which also displays the Common Operational Picture (COP) and streamlines the decision-making process. A third example where these functions can also be accomplished is the AEGIS Display System (ADS). The ADS console provides a capability so AEGIS operators can clearly view large-screen displays. The Command and Control Processor (C2P) is a message distribution system designed to control and manage the interfaces between the three tactical data links (Link-4A, Link-11, and Link-16) and the operator.

A final system that is part of the As-Is solution is the Global Command and Control System-Maritime (GCCS-M). This system satisfies the functions of Support

Sensemaking. GCCS-M fuses, correlates, filters, maintains, and displays location and attribute information on friendly, hostile, and neutral land, sea, and air forces. It integrates this data with available intelligence and environmental information in support of command decision-making. The user can use the data to construct tactical pictures using maps, charts, topography overlays, oceanographic overlays, meteorological overlays, imagery data, and intelligence information coordinated into a Common Operational Picture (COP) which can be shared locally or with other sites. Figure 24 is one display of many the modern version can provide.

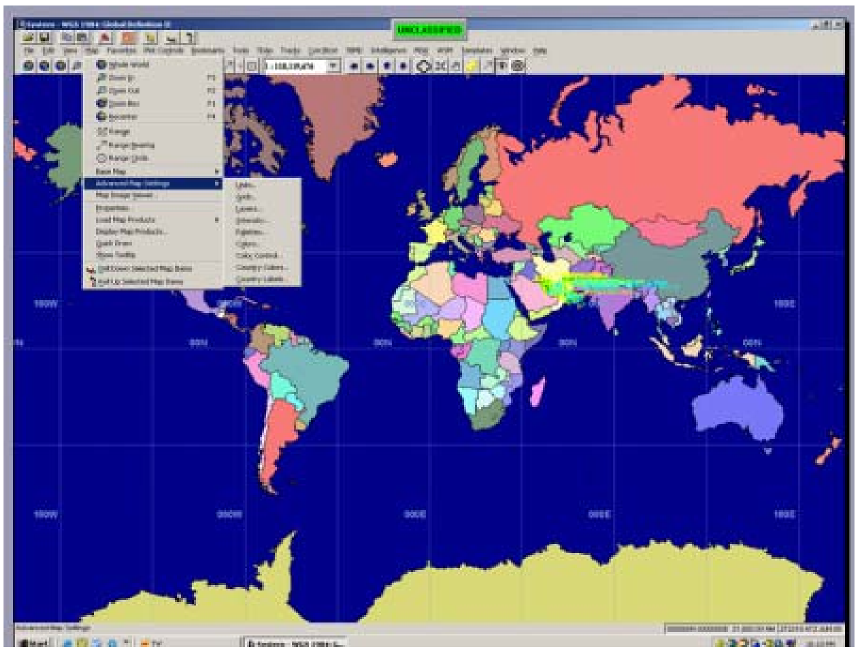


Figure 24. GCCS-M 4.X Display

This is a screenshot from a GCCS-M console. Maps are used with overlays to provide an operational picture to analysts in the CIC. [This Graphic was taken from Command and Control Programs, PMW150, GCCS-M Fleet Introduction Brief]

Many of these display consoles provide the means to visualize and interpret various kinds of data such as a map of objects, symbols, and track information. This information is provided to the commander for his decision making process. Figure 25 represents the worst case of how disparate systems have overwhelmed the environment for the operator doing C2 functions. The operator has to continually scan the various displays, each with different display methodology, as well as be attentive to auditory

stimulus. Not only are there various display types, most have their own associated input device such as a keyboard and mouse.

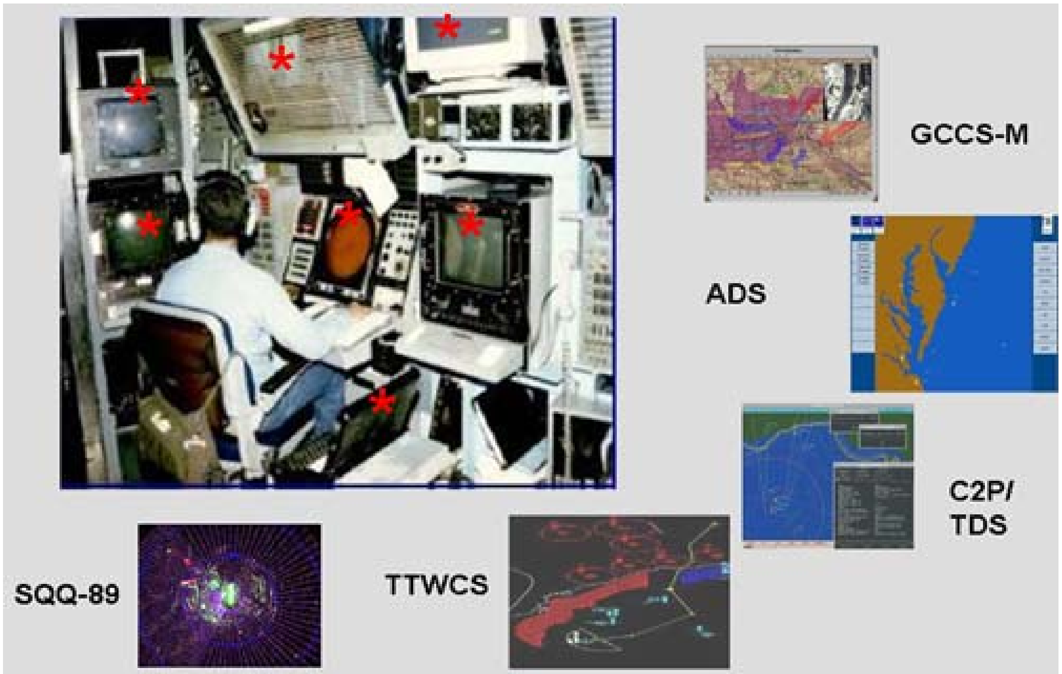


Figure 25. Multiple C2 Systems Displays

The larger picture depicts the overwhelming number of displays an operator can be asked to look at while doing his job. The smaller pictures show some of the types of disparate displays the operator could be looking at in the larger picture.

The point of naming all of these systems is to show C2 is currently supported in a large number of different ways. The idea here is: one needs to understand the information provided in all of these displays to perform good C2. To put it another way, Command and Control is currently performed by operators looking at many different systems, some of which were listed above, to gain an understanding of the operational picture. This understanding is then shared with the commander to proceed with the next C2 function Plan. A simplified graphical representation of these individual stove piped systems is shown in Figure 26. Each system provides the Collate and Correlate, Provide Contextualization, and Share Information functionality. Although the figure indicates distinct data sources, in reality each system may be accessing some of the same data and displaying the information in a unique way.

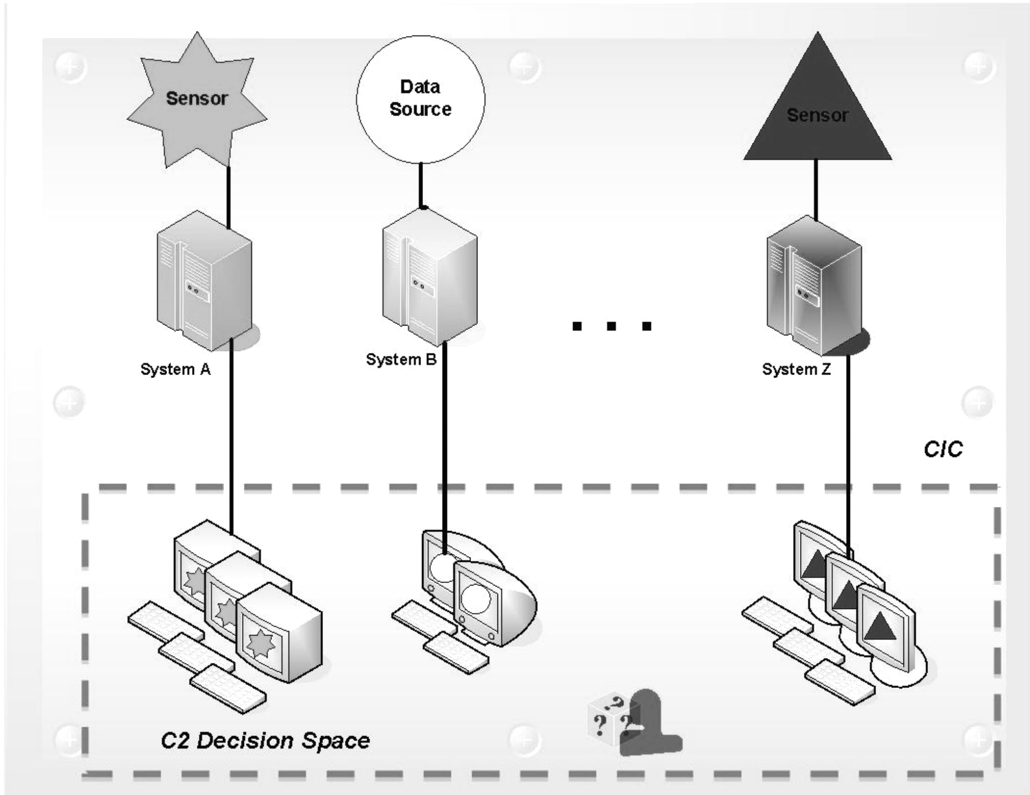


Figure 26. As-Is Design

This figure illustrates the current As-Is state. System A, B, through Z, represent the large number of different systems. Each system has its own sensors or data sources or both. These systems have individual processing systems and accompanying displays, in the CIC.

No single system in the As-Is architecture commonly addresses the Support Sensemaking sub functions Collate and Correlate, Provide Contextualization, and Share Information but rather these functions have been addressed in an ad hoc way by various systems. It is important to understand how these functions are addressed. Currently each system, with its own specific mission, Collates and Correlates its own information from data streams that are important to its specific mission and Provides Contextualization by presenting the information to the users by utilizing proprietary displays. This report considers Provide Contextualization of the As-Is architecture to include the user gaining an understanding from each of the relevant stove piped systems with C2 elements. Each system is responsible for sharing its own information. For example, Aegis Weapon

System (AWS) uses Cooperative Engagement Capability (CEC) and Tactical Digital Information Link (TADIL A and J). Also, non-tactical information sharing is done via chat and Common Operational Picture synchronization tools. So, although in many cases a commander may have used various systems in order to gain an understanding of the operational picture, this deeper understanding is unable to be shared effectively.

2. Hybrid

The Hybrid architecture, shown in Figure 27, expands and modifies the current architecture in the areas of data and information storage, display methodology, and how the information is shared.

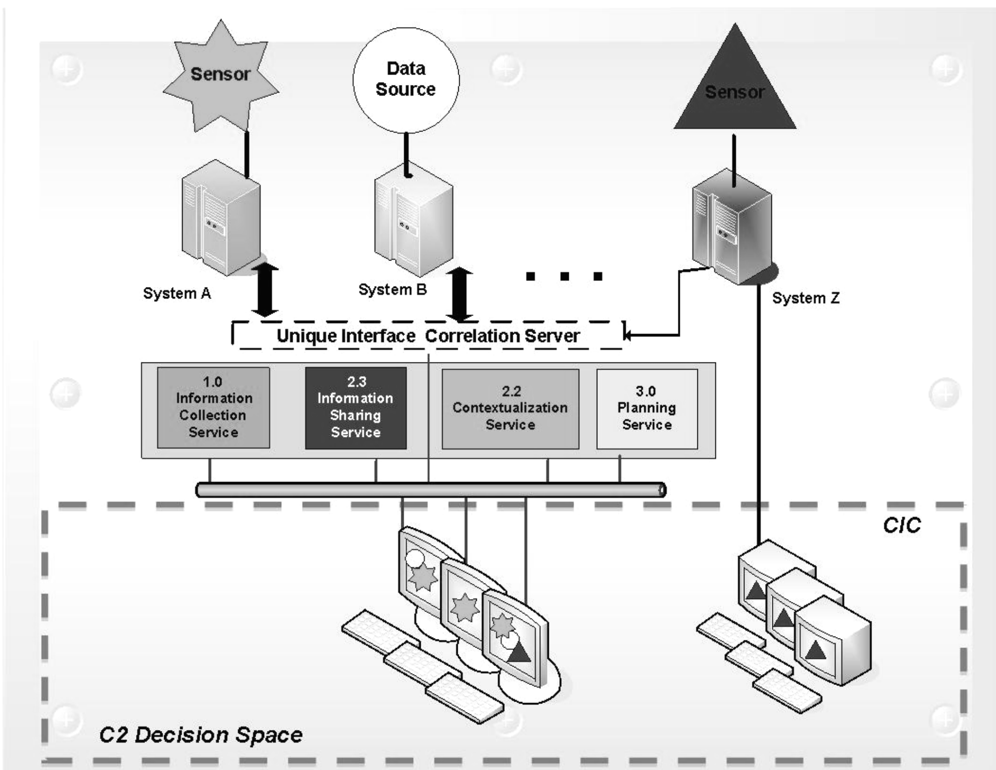


Figure 27. Hybrid Design

The graphic illustrates how the Hybrid system takes the information provided from the sensors and processing systems in the As-Is architecture, combines, and sorts this information. This data can be viewed on a single display. However, each system will also be able to maintain an independent display when their unique view is deemed mission critical. In this graphic, System Z represents a legacy system that will maintain its current display due to complexity or need.

The first major aspect of this alternative is the Unique Interface Correlation Server (UICS) and the associated unique Interface Processors for each interface. Each Interface Processor accepts the data from interfaces such as data links, sensors, etc., and converts it into standardized data formats. The Interface Processors add an additional layer at the interface level but this reduces system complexity later by using standard data formats instead of proprietary data formats.

The UICS accepts the standardized data from various Interface Processors, and organizes the mission relevant data into clear and concise format (collate). During the collation, redundant data or data conflicts are tagged for later review and de-confliction. The UICS will also link the data (correlate) to create meaningful relationships.

The assembled data is analyzed and mission specific associations are created then monitored to enhance operational assessment of the information as a whole. The information is available on operational displays as well as for collaboration with other operators.

As the data and information are processed and monitored, the operators may configure alerts to be generated based on mission parameters or pattern changes. The alerts may be mission specific or global across multiple mission scenarios. Contextualization provides for a common visualization which affords customizable views allowing the operators to focus on mission specific data. A geospatial reference is generated for accurate positional orientation and the data is set to a standard ontology. The displays are tailored to display only relevant information based on user set criteria. The new Provide Contextualization function is capable of linking data from all the relevant C2 systems and a unified view is achieved.

The key is there are now fewer displays that need to be consulted in order to get an understanding of the operational picture. This is designed to make it easier for the analyst to form a clear operational picture quickly. This view of the operational picture can then be shared with the commander by showing him a reduced number of information streams, which make it easier to understand, and allows him to quickly move on to the C2 Planning function.

The Hybrid system utilizes a mixed approach for the Share Information function. Each individual system's capability to share information will need to be leveraged. Either CEC or LINK could be used to maintain interoperability with legacy platforms and include a new standardized real-time data distribution service.

3. Global Understanding Network (GUN)

The Global Understanding Network solution, shown in Figure 28, expands and modifies the Hybrid architecture in the areas of data and information storage.

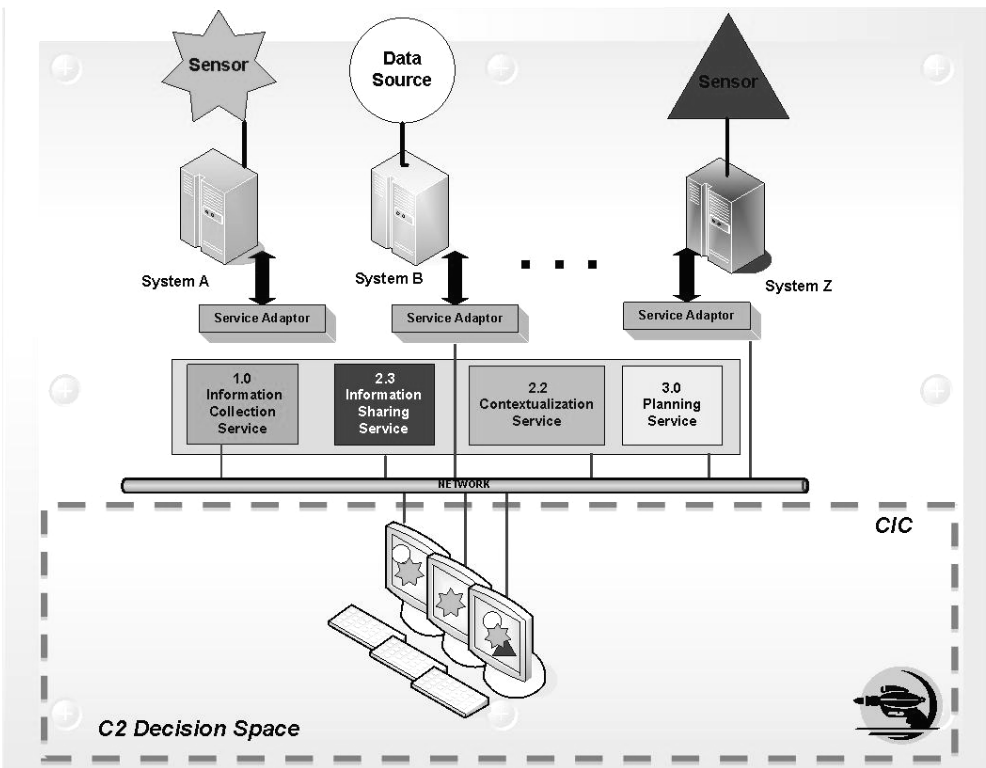


Figure 28. GUN Design

The GUN takes all of the data sources of disparate systems and makes all of this information available on each operator's display. This means the displays are fully customizable to allow the user to see any information that has been collected clearly.

This solution replaces the unique UICS of the Hybrid solution with service adapters. The service adapters are used to put all the data into universal formats. This data is then stored and organized by its type. This completes the Collate and Correlate function in a unified way. The utilization of adaptors and the standardization of services

align this alternative closer to the Services Oriented Architecture (SOA) model. SOA is a design model based on reuse, scalability and interoperability. The service adaptors remove the point-to-point stove pipe connections of the legacy systems.

In the GUN design, all of the information collected is available on a single universal display that connects directly to a standardized and organized data repository. This allows the operator to customize their views displaying any subset of the data collected. All the information collected is available to each operator and they can customize their views to allow fast access to all the information that is relevant to them. Also, this setup allows views to be saved to the data repository and shared with other analysts. For collaboration, areas on each display can be marked for sharing, allowing it to be viewed on other displays by other operators who may need the information. Provide Contextualization is thereby completed with all available data not just data present in one C2 systems sphere of influence.

The GUN also provides for an open standardized way to Share Information. The customized view created by the Collate and Correlate function and modified by the user in the Provide Contextualization function can be shared globally with others. This is where this architecture received its name. The understanding that has been created by the system and tailored by the operator is now available on the Global Understanding Network.

Through alternatives generation and feasibility screening, three architectures have been defined that answer the second research question, “What architectures can be defined that address common requirements of USN C2 decision making, specifically related to visualization?” The three C2 architectures were the As-Is, the Hybrid, and the GUN. The AS-IS architecture defines the current visualization methods with a variety of displays showing different data or the same data different ways. Two new architectures focus on C2 with an emphasis on improving C2 through visualization by providing common visualization techniques and concepts, either in part as with the Hybrid or as a complete solution as with the GUN.

D. MODELING AND ANALYSIS

Modeling of the information flow was used in determining which of the feasible alternatives is recommended for further analysis. Modeling and analysis focused on the visualization aspect of the Support Sensemaking function, how it affects information flow, and ultimately decision making. Modeling and analysis was performed on the three alternatives determined by the feasibility screening as part of the tailored SEDP. These three alternatives are: As-Is, Hybrid, and Global Understanding Network (GUN).

1. Modeling Approach

The modeling approach was to model cognitive aspects of C2 with an objective to measure and compare the three alternatives. An encountered challenge was the comparison of non-existent alternatives, Hybrid and GUN, to the existing alternative, As-Is. Because data was limited or does not exist for these non-existent alternatives, the following approach was used to effectively evaluate the performance of these non-existent alternatives.

Creating a notional model for the As-Is and running a simulation to obtain values for the key performance parameters established a baseline. This model served as a template and was also used to model the other alternatives. Only the information flow was altered for each alternative. The established baseline was used to compare the performance of the new, non-existent alternatives. The key performance parameters included were the ones directly addressing the timeliness and decision factors associated with the current operational requirements. The performance data from each simulation was recorded and used in the comparison of the alternatives. The results from the simulation were compared against related MOEs and further analyzed. Table 7 shows the selected items from Table 4 used in the model. Not all MOEs were considered during evaluation; the most important MOEs considered were the ones that directly impact the response timeliness and the accuracy of decisions.

REF	Function	Objective	Evaluation Measure
A2.1	Sensemaking	Reduce uncertainty	Number of failures in making a decision within an allotted time / Number of total decisions. (less is better)
A2.2	Sensemaking	Decrease reaction time	Average elapsed time for decision (secs). (less is better)
A2.3	Sensemaking	Increase quality of information produced	Average number of data elements that enhance the decision above what is required. (less is better)

Table 7. Selected Measures of Effectiveness from Evaluation Measures

These measures were selected for the models due to their relevance to the timeliness and accuracy of the decision making process.

2. Arena Model Description

Rockwell Automation's Arena was chosen as the tool to create the models and run the simulations. Arena was selected because of its flow chart based approach in constructing models. This kind of approach is well suited for modeling of information flow and allowed for measures to be taken at chosen locations in the C2 architectures. A storyboard of the model is shown in Figure 29.

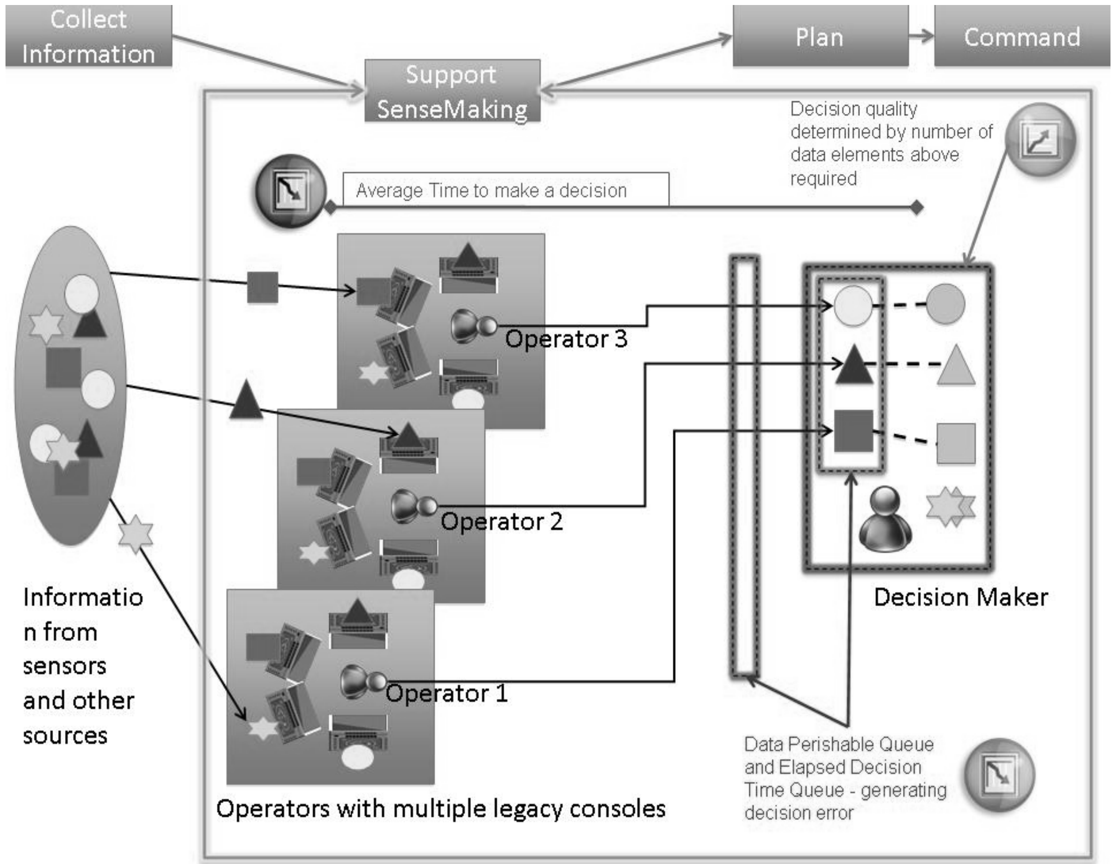


Figure 29. Graphical Representation of the As-Is Model

In the As-Is architecture, numerous operators receive and interpret information from multiple sensors and data sources. The differences in visualization systems require users to reacquaint themselves when moving between displays possibly causing delays.

In order to make a decision, key pieces of information are required based on the situation. Ten data elements representing information needed to make a decision were used to model the As-Is. This number was chosen after evaluating the mission threads discussed earlier in this report and determined to be adequate for a notional model. These data types were randomized with a uniform distribution and had a random arrival rate with an exponential distribution with a three second mean. Data types were routed to specific systems in front of one of three operators. Each operator had four consoles to operate. Since the operator had multiple interfaces, a value was calculated relative to the

distance between the system the operator was on and the system he or she was moving to. This value represented the cost in time for repositioning and re-acquaintance with the other system.

The operator passed, or relayed, the information to the Tactical Action Officer (TAO) if needed. The relaying of information prevented the operator from handling other incoming information at his workstation once the relay started until it was complete. Similarly, another operator could not pass information to the TAO if he was busy talking with another operator. Think of this as preventing multiple operators from yelling information to the TAO at the same time making the information unintelligible. Updates to perishable data were accounted for by randomly routing half of the data elements already held by the TAO to him as updates to existing information. This construct is consistent with behavior observed during similar command and control field experiments where information was passed to a decision maker [Shattuck and Miller, 2007].

This process repeated until either all required pieces of information were obtained or until a specified time value expired indicating the mission required a decision despite not being optimal. This threshold was obtained from doctrine during the mission thread analysis. Decision quality was measured on how many of the ten data types were included in the TAO's decision making process. Decision error was determined if time expired to make a decision and not all required data elements were present or if an expired data element was processed.

The models for the other alternatives, Hybrid and GUN, functioned identically but the flow of information was changed to represent their respective architectures. The model for the Hybrid had two consoles per operator versus the four in the baseline. The operator in this alternative was still handling the same information but only had to switch between two displays. The model for the GUN had a single unified display per operator with all the information flowing to it. This approach ensured the captured data was isolating the objective of the models.

The concept of modeling information flow related to C2 on-board a surface combatant is complex due to the many permutations required to actually represent all scenarios possibly encountered. The model was purposefully isolated on the notional operator handling of information related to multiple interfaces and not made to represent an actual CIC. The model does not accurately reflect the number of operators in the expected environment, the actual number of sensors on-board ship and the respective data output, or variation in operator behavior such as alertness or distraction. These conditions could be areas of future modeling efforts if deemed necessary however were considered unnecessary and potentially convoluting to the model's results.

3. Data Elements

Data elements for the model were decided upon and held constant for all three simulations. Only the flow of information was changed to represent the different alternatives. These data elements held constant for each alternative were: arrival rate of data elements, the number of data elements contributing to making a decision, the data elements required to make an accurate decision, the time involved for an operator to switch from one workstation to another, the time required to relay information to the decision maker, the maximum time before information expired, and the maximum time allotted to make a decision. Table 8 contains a description for each data requirement.

Data elements for the analysis were decided upon prior to constructing the model and appropriate data recording mechanisms were employed to collect data. The data collected for analysis was: time to make a decision, number of decision data elements used in the decision, number of decisions made, and number of decision errors. The collected data was used to determine average time to make a decision, decision quality, and probability of decision error.

Data elements (model input)	Value
Raw information arrival rate	Exponential distribution (3 seconds)
Number of data elements in mission thread	10
Number of required data elements	5
Time to switch between consoles	Normal distribution (mean: 2 x number of consoles changed, standard deviation: 1.5) in seconds
Time to relay information to TAO	Normal distribution (mean: 2, standard deviation: 1.5) in seconds
Maximum time for data expiration	30 seconds
Maximum time allotted to make decision	90 seconds
Data elements (model output)	**Measure**
Average time to make decision	Sum of decision times / Total number of decisions
Quality of decision made	Average number of data elements used in decision
Probability of decision error	Number of decision errors / Total number of decisions

Table 8. Data Elements for Modeling Information Flow in Decision Making.

Data requirements for inputs and outputs were decided and held constant for all simulations. Only the flow of information was changed to represent the different feasible alternatives.

4. Results

In the As-Is system, the operators' ability to obtain information from several different visualization displays established a baseline for the time it takes to make a decision. The hypothesis was: a standardized visualization display would reduce the time an operator spends in obtaining the information required by the decision maker when compared to the baseline. In other words, the time to obtain information an operator is responsible for via a single, standardized visualization display is less than the time to obtain the same information from several different systems. This affects the overall time to make a decision.

Average time to make a decision was recorded and compared for each alternative. The decision quality was determined by how many additional non-required, but enhancing, data elements were part of the decision. Decision quality was recorded for each alternative to ensure it did not decrease. Likewise, a decision error was captured

indicating a decision could not be made in the maximum time allotted and a required data element was missing, or if an expired data element was processed. A reduction in either of these measures would be considered unacceptable if the lower value did not meet the threshold requirements of the respective MOEs.

Although the specific results used in the alternatives analysis were for a two-second operator adjustment penalty, the following graphs show a range of the modeling results from one to three seconds with a half second interval. This was done to gain a better understanding of the results and evaluate how they vary as a result of operator performance differences based on experience levels, fatigue, or distractions. The graphs show how the alternatives compared to the As-Is baseline.

Figure 30 shows a graph of the modeling results for average time to make a decision over this range. The results show a possible decrease of almost three seconds in the average time to make a decision with an experienced operator when incurring a one second penalty. The potential benefits continue to increase as the operator adjustment penalty increases. This suggests the average time to make a decision would be reduced, and inexperience or distraction counteracted with the reduction of displays.

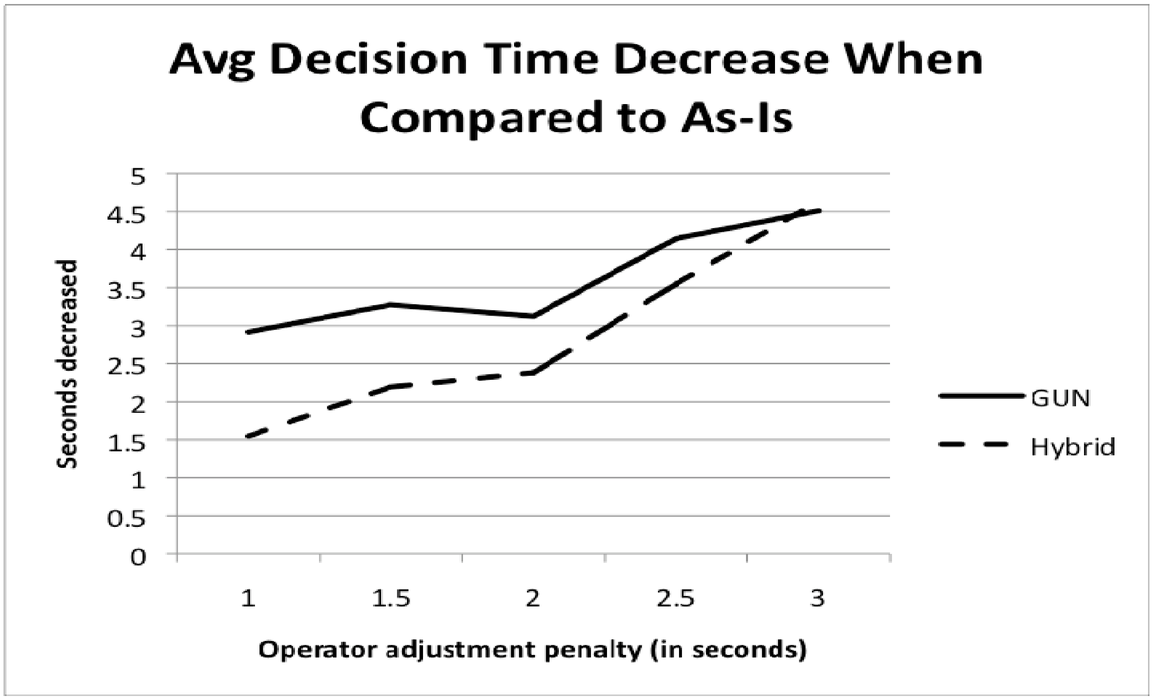


Figure 30. Modeling Results for Average Decision Time

A comparison of the average decision time from the As-Is to the GUN and Hybrid alternatives showing a decrease in average decision time using the alternatives with operators with higher adjustment penalties.

Figure 31 shows a graph of the modeling results for average decision quality. The results show no immediate benefit in the average decision quality with an experienced operator when incurring a one second penalty. However, a small benefit is shown at the two second penalty range. Substantial benefits are achieved above the two second penalty range and continue to increase as the operator adjustment penalty increases. This suggests the average decision quality would be increased, and inexperience or distraction counteracted with the reduction of displays.

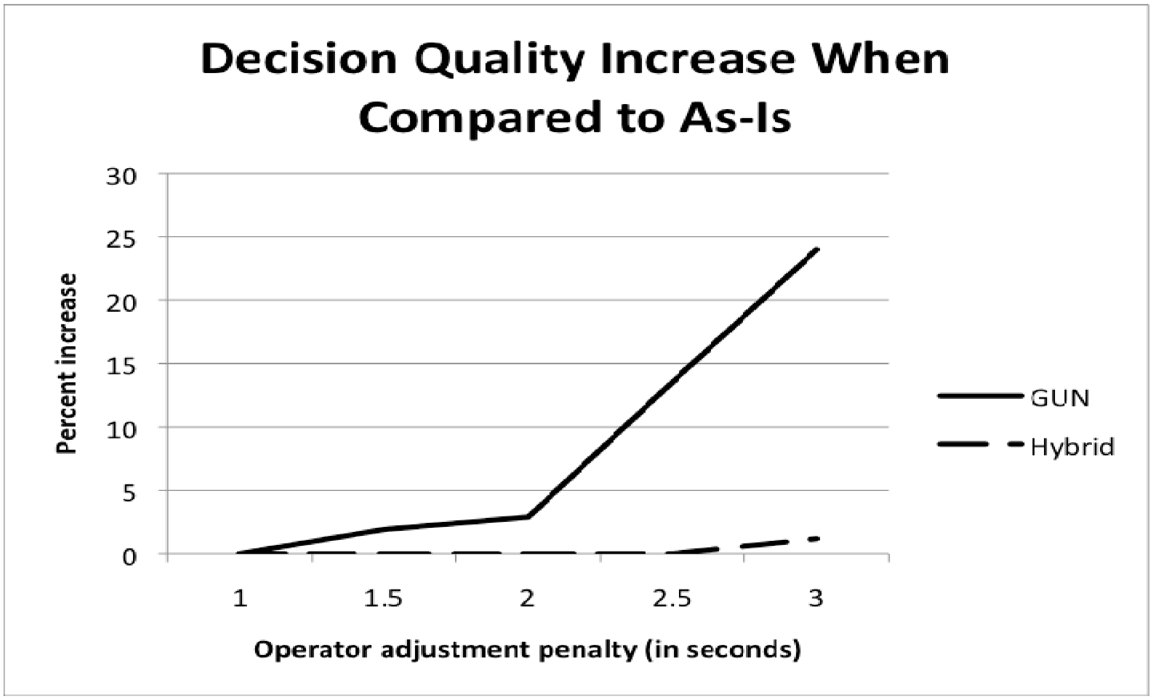


Figure 31. Modeling Results for Decision Quality

A comparison of the decision quality from the As-Is to the GUN and Hybrid alternatives showing an increase in decision quality using the alternatives with operators with higher adjustment penalties.

Figure 32 shows a graph of the modeling results for probability of decision error. The results show no immediate benefit in the probability of decision error with an experienced operator when incurring a one second penalty. However, a small benefit is shown at the two second penalty range. Substantial benefits are achieved above the two second penalty range and continue to increase as the operator adjustment penalty increases; this suggests the probability of decision error would be reduced, and inexperience or distraction counteracted with the reduction of displays.

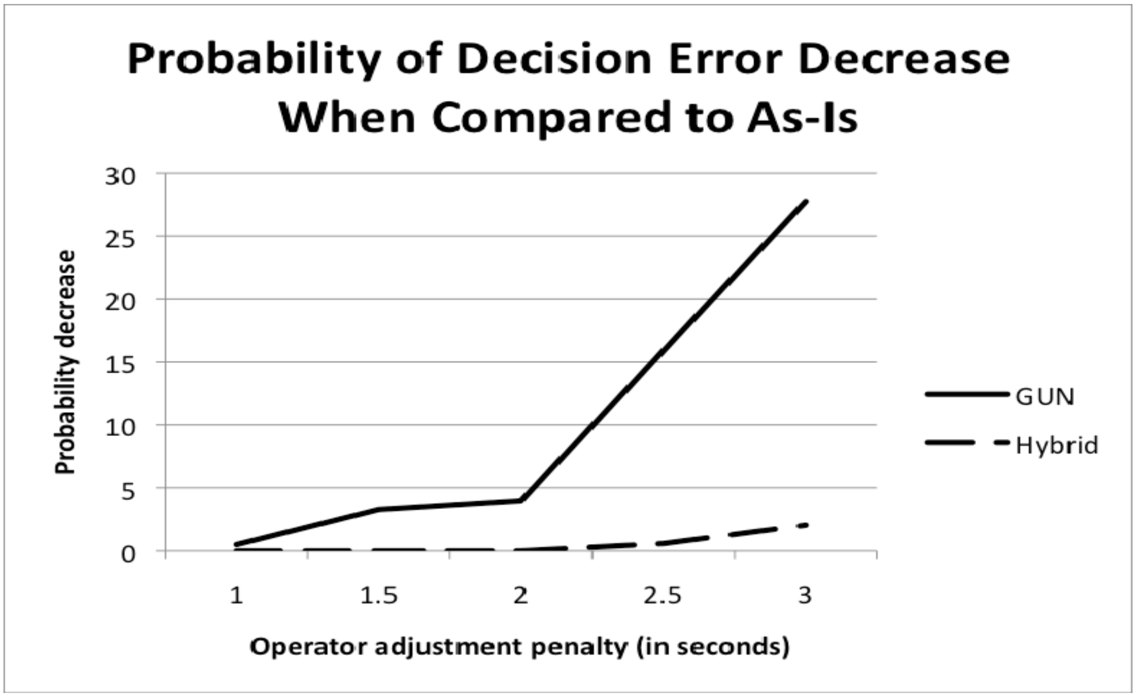


Figure 32. Modeling Results for Probability of Decision Error

A comparison of the probability of decision error from the As-Is to the GUN and Hybrid alternatives showing a decrease in decision error using the alternatives with operators with higher adjustment penalties.

The data from the modeling results used in the alternative analysis were the respective values for a two second operator adjustment penalty. This penalty value was chosen as a result of direct operator observation during model design. Table 9 contains the values for the two second penalty results.

Data Requirement (Results)	As-Is	Hybrid	GUN
Average time to make decision	55.90 sec	55.16 sec	52.78 sec
Quality of decision made	67.16%	70.66%	70.06%
Probability of decision error	0.2567	0.2168	0.2171

Table 9. Detailed Modeling Results for the Two Second Operator Adjustment Penalty

Data requirement scores that were recorded from the modeling results are used for alternative comparisons

The analysis in modeling and simulation answers the third research question, "Can decision making quality, accuracy, and timeliness be quantified and modeled within unified C2 architectures?" Models of the three alternatives were created to measure decision quality, accuracy, and timeliness. The models allowed for variability in information arrival rate, operator handling time, and decision maker processing time. These variables made it possible to measure decision making quality within an allotted time and decision accuracy based on available information within a specified period.

IV. ARCHITECTURE ANALYSIS

A functional decomposition was performed for the Support Sensemaking function of the Common C2 System. Following functional analysis, the Value System Design process was used to create evaluation measures addressing stakeholder requirements and later to be used to assess and compare performance of the alternatives. The Hybrid and the GUN remained as the most beneficial alternatives based on the Feasibility Screening. These alternatives have been created to exploit the architecture developed from functional decomposition and improve the Sensemaking functions by combining disparate and duplicative systems and improving visualization. As a result, decisions will be facilitated more quickly, with less error, and with higher quality. This was demonstrated through modeling and simulation.

In this section, the benefits of the Hybrid and GUN architectures are discussed in terms of efficiencies through training and their performance in modeling. A brief discussion on projected benefits that have yet to be validated is also included. The result is the architectural analysis recommendations. This is where it is explained why the GUN architecture is considered the best option to pursue based on the analysis done so far. This process is shown in Figure 33.

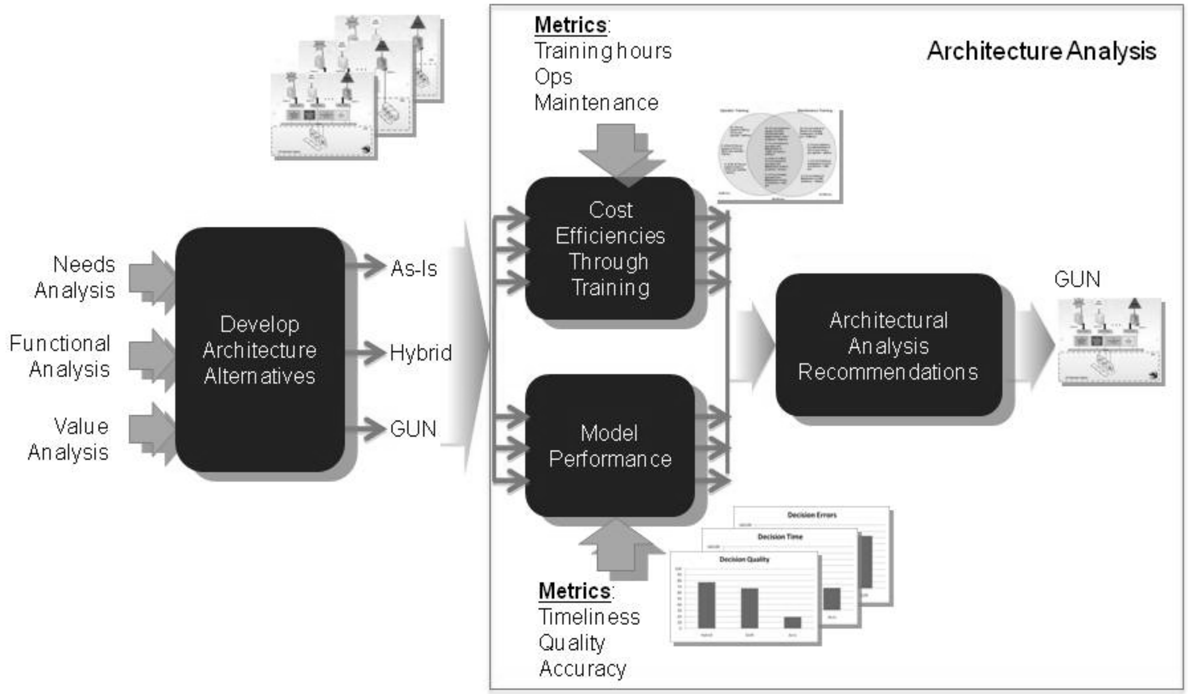


Figure 33. Architecture Analysis Flow

This illustrates the flow of the architecture analysis. The needs, functional, and value analyses lead to the development of Architecture Alternatives. The As-Is, Hybrid, and GUN are discussed in terms of training efficiencies and modeling performance. Finally, recommendations are given based upon the information gathered.

A. ARCHITECTURE ANALYSIS LIMITATIONS

The Hybrid and the GUN architectures were further examined using modeling and analysis. Because limited unclassified data exists on the As-Is C2 architecture, a notional process model for a typical surface combatant CIC was used for simulation. The model simulated user interaction with the number of displays in As-Is, Hybrid, and GUN architectures to see the impact of multiple displays on decision making. The results gathered were used to compare the two architectures against each other and the As-Is architecture. The MOPs related to decision quality, error, and time, were used. The results are discussed in the sections below.

Another constraint of the model was the inability to model human cognition effectively. Major benefits are believed to be gained by facilitating human cognition through better organizing data, eliminating redundancy, and automatically flagging disparity. This is supported by research done by William Hick and Ray Hyman. Hick's

Law states the time it takes to make a decision is based on the number of alternatives; by reducing redundancy, the number of perceived alternatives is reduced and a gain should be made [Card, 1983]. The best way to model the benefits of better organized data on human cognition in a particular system is to create a prototype of that system and create use cases. The use cases would then be run in the As-Is state and then on the prototype of the new system to determine performance.

Finally, this paper does not address Life Cycle Cost Estimates (LCCE). Cost estimates by analogy were considered earlier in the SEDP to estimate costs for the Hybrid and GUN architectures. However, this did not show promise because it became impossible to find a similar enough architecture to create a meaningful comparison. The main reasons were: the new architectures stress new centralized data and information storage and processing, combining all disparate information systems, the emphasis on processing information in universal formats, and the new interfaces that have yet to be defined. The C2UniArch team analyzed the training benefits. It is estimated the training requirements will be significantly reduced compared to the As-Is architecture.

B. ANALYSIS OF ALTERNATIVES

1. Model Performance

The modeling results provide quantitative data to determine if there are discernable benefits to the alternate architectures. Table 10 indicates there may be advantages to these alternatives.

Attribute	As-Is	Hybrid	GUN
Average time to make decision	55.90 sec	55.16 sec	52.78 sec
Quality of decision made	67.16%	70.66%	70.06%
Probability of decision error	0.2567	0.2168	0.2171

Table 10. Raw Data Matrix

The raw data matrix summarizes the model-predicted performance measures for each alternative using the two second operator adjustment penalty from the modeling section. For a more detailed discussion of these results see the Modeling and Simulation section.

The raw data was transformed into a utility value and charted. The utility value may be thought of as the amount of benefit gained by an alternative. The utility value is scaled from 0 to 100 to make comparisons easier. Each attribute that was investigated has its own function to convert the raw data to the utility score. In order to ensure the appropriate function was used, the three attributes were analyzed. Also stakeholders' consultation and concurrence was sought for all utility curves.

The decision quality utility function is piece-wise linear as a result of discussions with the stakeholders; it was decided once a reasonable decision quality (50%) was reached, there was a steady gain in value until 100% decision quality was reached. When transforming the raw data into utility values it was determined at least 50% decision quality must be reached. Decision quality of 50% or less was considered to be of no value by the stakeholders. There is no point at which the stakeholders consider there to be a steep change in the value of decision quality within this range. Figure 34 depicts the Utility for Decision Quality.

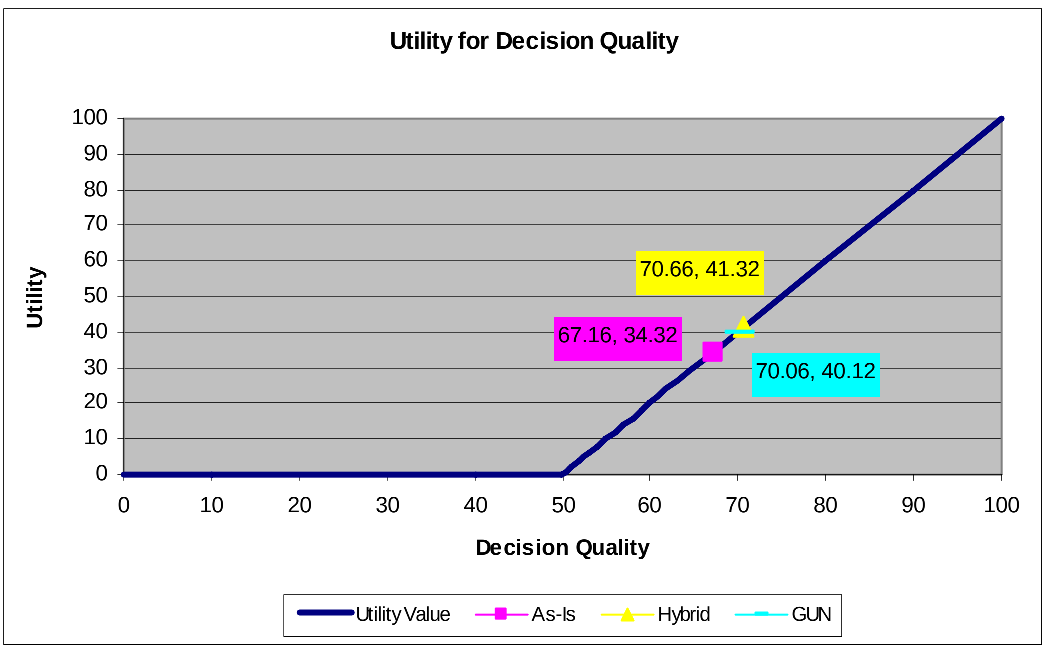


Figure 34. Decision Quality Utility

Decision Quality is the average score indicating the number of model data points used to make a decision. This graph shows the utility values. There is no utility from 0% to 50%. After 50%, the utility increases linearly.

The stakeholders also indicated decisions with less than 50% quality did not have a positive impact on mission accomplishment. A decision with low quality is just as likely to decrease the chance of mission success as to increase it. Once decision quality increases above 50%, value slowly accumulates. This is because the chance for increasing the likelihood of mission success is increasing with higher quality decisions.

Referring to Figure 35, it can be seen that the Hybrid affords the best benefit by scoring the highest utility value. With decision quality, the higher values are desirable as more data points are involved in the decision making. The utility function used to calculate the utility value shows the Hybrid to have the best performance; however, under examination the raw data for the Hybrid and GUN are very close in value. Both the Hybrid and the GUN have a distinct benefit over the As-Is in decision quality.

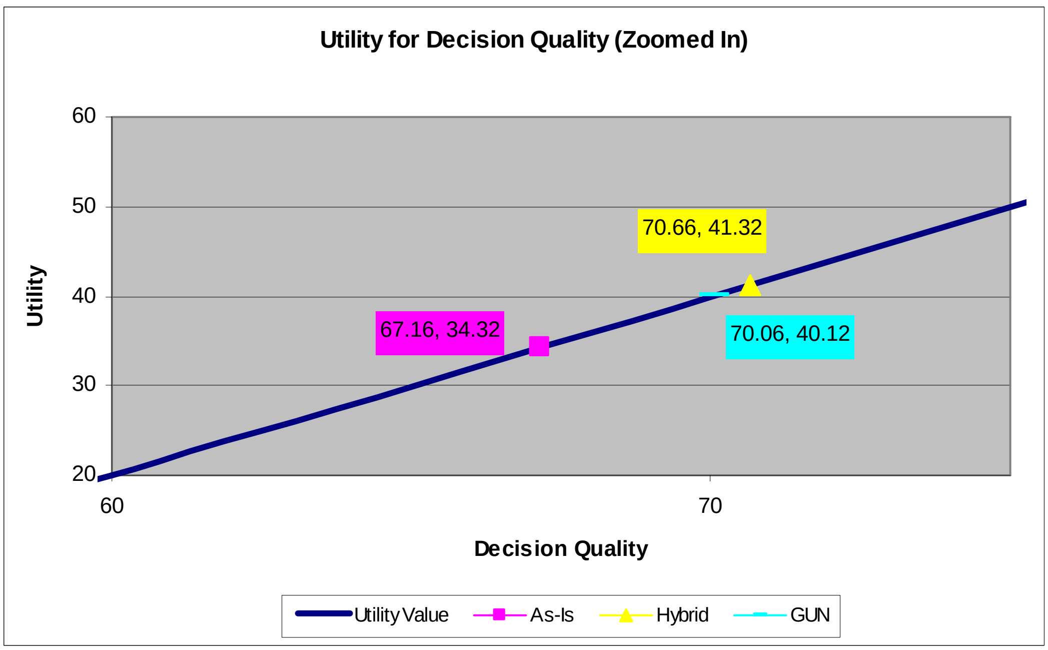


Figure 35. Decision Quality Utility Zoomed In

Decision Quality is the average score indicating the number of model data points used to make a decision. This graph is a close-up between 60 and 75 percent to emphasize the difference between the alternatives.

When transforming the raw data into utility values for decision error, it was determined if over 40% errors were reached, the decision based on this information could not be trusted and gave a zero utility value. A value of 100 is not reached until the

system is error free. However, even with a few errors, it is likely a good decision will still be reached, so a curved function was used. The As-Is clearly performs more poorly than the Hybrid and GUN. At 25-30% errors a steep drop off begins as suggested by the stakeholders. After reaching this many errors, the resulting decision will quickly lose reliability.

Decision Errors are the percent of errors each alternative had during the simulation. The Decision Errors are again normalized and scaled to a utility value. In this case, the lower the raw data value, the greater the utility value score. Examining Figure 36, both the Hybrid and GUN score equally well in the utility value. While there is no clear distinction between them, they both score better than the As-Is.

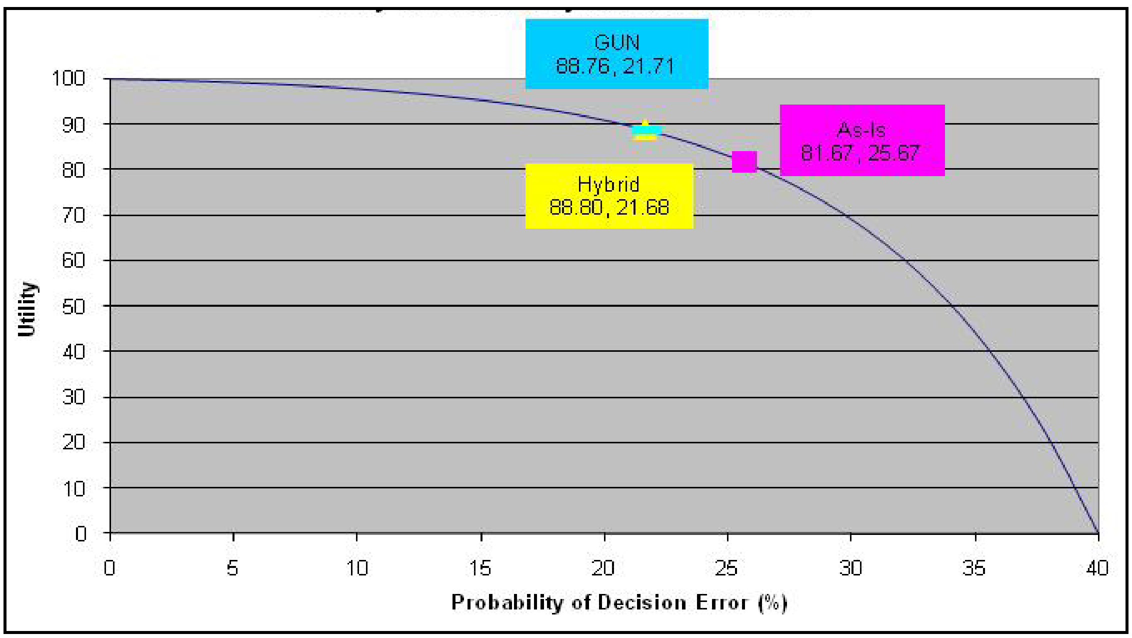


Figure 36. Decision Errors Utility

Decision Errors is the percent of model simulation errors for each alternative. The As-Is clearly performs more poorly than the Hybrid and GUN.

When transforming the raw data into utility values for decision time, it was decided, after considering mission threads like Cruise Missile Defense, decision making taking longer than 120 seconds are of no value. After 120 seconds it is very likely the defender will have already been hit. Decisions made in less than 60 seconds are usually in time and are of value. Between 60 seconds and 120 seconds there is a steep slope,

which represents the decision coming too late to be fully effective. In the case of Cruise Missile Defense, it represents a missile reaching the defender before being thwarted. There is a steep drop off that begins between 80 to 90 seconds because a cruise missile has a good chance of reaching its target by that time.

Decision time is the average time for each alternative to come to a decision from the model simulation. The decision time utility value is higher when the average decision time is shorter. The decision time Utility, shown in Figure 37, shows no architecture performed significantly better than any other, however, the GUN slightly outperformed the other alternatives. It is important to note in some instances every second can count. When dealing with Cruise Missile Defense, a second could mean the difference between safety and loss.

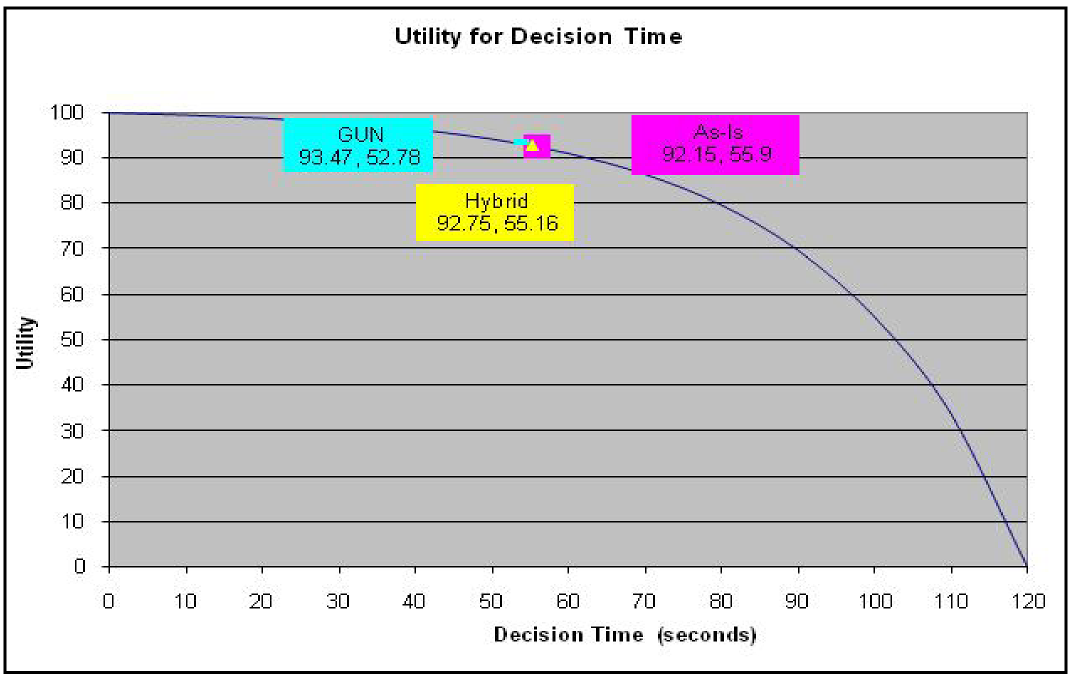


Figure 37. Decision Time Utility

Decision Time is the average time to make a decision for each alternative. This curve is strongly influenced by the Cruise Missile Defense mission thread.

2. Model Attributes Scoring

Another scoring criterion required prior to the completion of the Decision Matrix is the swing weighting for each attribute. Swing weights were used to rank and weigh the critical attributes against each other based on the best and worst case scenarios [Clemen and Reilly, 2001]. Using the raw data, the worst case scenario (“benchmark”) is developed by aligning the worst data point of each attribute and assigning to it a score of 0. Then for each attribute, the benchmark is modified by ‘swinging’ the worst data point of that attribute to the best data point, creating a hypothetical alternative. These hypothetical alternatives essentially have only one critical attribute at its best; this forced the stakeholders to rank and rate (assign points) to alternatives or critical attributes which dominated their decision making process. These rates were then normalized and weights were calculated. The results are shown in the Table 11.

	Consequence to Compare	Rank	Rate	Weight
Benchmark	Q=67.16%, DE=25.67%, DT=55.9s	4	0	0
Quality	Q=70.66%, DE=25.67%, DT=55.9s	2	25	0.13
Decision Error	Q=67.16%, DE=21.68%, DT=55.9s	3	75	0.38
Decision Time	Q=67.16%, DE=25.67%, DT=52.78s	1	100	0.50
		SUM	200	1.00

Table 11. Finalized Swing Weights

Q represents Decision Quality, DE represents Probability of Decision Error, and DT represents Decision Time. The Benchmark entry shows a culmination of the worst performance found in each category. Decision Time has a very high weight followed by Decision Quality and Decision Error with similar rates.

To compare the alternatives, an overall value was required. By combining the Utility Function and the Swing Weights, the Raw Data Matrix was refined into a Decision Matrix. The Decision Matrix is shown in Table 12, and the values shown are a result of the Utility Value multiplied by the weights found in the Swing Weights Table. The product of these calculations was summed for each alternative to arrive at a total value score and is provided in the Decision Matrix Table. From best to worst values, they are: GUN 85.03%, Hybrid 84.84%, and As-Is 81.17%.

The analysis presented here answers the fourth research question, “Does a unified C2 architecture improve decision quality, accuracy, and timeliness?” In this section, the

results for decision quality, accuracy, and timeliness were analyzed and the three alternatives were compared against each other. These results suggest a unified C2 architecture improves these decision-making qualities. However, there was not a very large variance in the results. The last question that needed to be answered is, "Does a unified C2 architecture reduce training costs?" This question gives more information which will help differentiate between alternatives when performing architecture selection.

		Alternatives		
Evaluation Measure	**Weight**	**As-Is**	**Hybrid**	**GUN**
Quality of Decision (%)	0.13	34.32	41.32	40.12
Probability of Decision Error (%)	0.38	81.67	88.80	88.76
Decision Time	0.50	92.51	92.75	93.47
Total Value Score	1.00	81.17	84.84	85.03

Table 12. Decision Matrix

The weights calculated from the stakeholders input were used to calculate the attribute weights. These results were then multiplied by the Utility Value. The results were then summed for each alternative to yield the Total Value.

3. Training Benefit Analysis

An examination was conducted to determine if there was an added benefit with respect to system course training requirements for operators and maintenance for each alternative. This could identify cost efficiencies for each alternative. The analysis recognized the correlation between hours spent in training and cost; the exact determination of quantifiable cost was deferred for future studies. The examination began by looking at the As-Is architecture on board the most recent Arleigh Burke-class DDG, and collecting information to see how much training was required for the ADS, GCCS, C2P, TTWCS, NFCS, and the SLQ-32. Since there are a number of C2 systems on board this class of ship, it was decided to scope the examination to those systems based on available data.

Intensive research and the gathering of unclassified, readily available resources were performed for this examination. Manning requirements spreadsheets provided by PMW 150 for DDGs were used to approximate how many system operators and

maintenance personnel are required for specific systems onboard that particular class ship. The Navy Enlisted Manpower, Personnel Classification and Occupational Standards Volume II publication was used to research the specific systems personnel were slated to be trained on. The Catalog of Navy Courses (CANTRAC) was used to gather specific system course lengths in training hours per person required for that specific system.

Assumptions were applied to multiple variants of C2 systems. For example, there are multiple AEGIS systems operator and maintenance courses offered. If a maintenance course length was not found, it was assumed that the length of the course was the same as similar maintenance courses. For instance, the AEGIS operator course is approximately sixteen days which is also the assumed length of the maintenance course for the AEGIS display console.

Operator, maintenance, and combined operator and maintenance courses required for the most recent Arleigh Burke-class DDG ship exceed over 45,000 hours combined for those systems. Figure 38 represents the approximate manning requirements and course training hours for those systems. The left side, for example, represents operator training for the ADS, GCCS, and LINK. Forty- five Operations Specialists (OSs) are trained on the ADS system with a course length of 152 hours [DDG Manning Requirements 2009; CANTRAC vol. II 2009]. When including over 45 OSs trained to operate this console, this sums up to over 6,800 hours of AEGIS operator training for this platform. Six of the 45 are trained on GCCS-M with a course length of approximately 208 hours and four of the 45 are trained on Link-11/16 (C2P) with a course length of 152 hours [Activity Manpower Document 2009; CANTRAC vol. II 2009].

The center of Figure 38 represents the personnel trained to both operate and maintain ADS, TTWCS, NFCS, and the SLQ-32. These specific systems altogether sum up to over 20,000 hours of training per DDG ship.

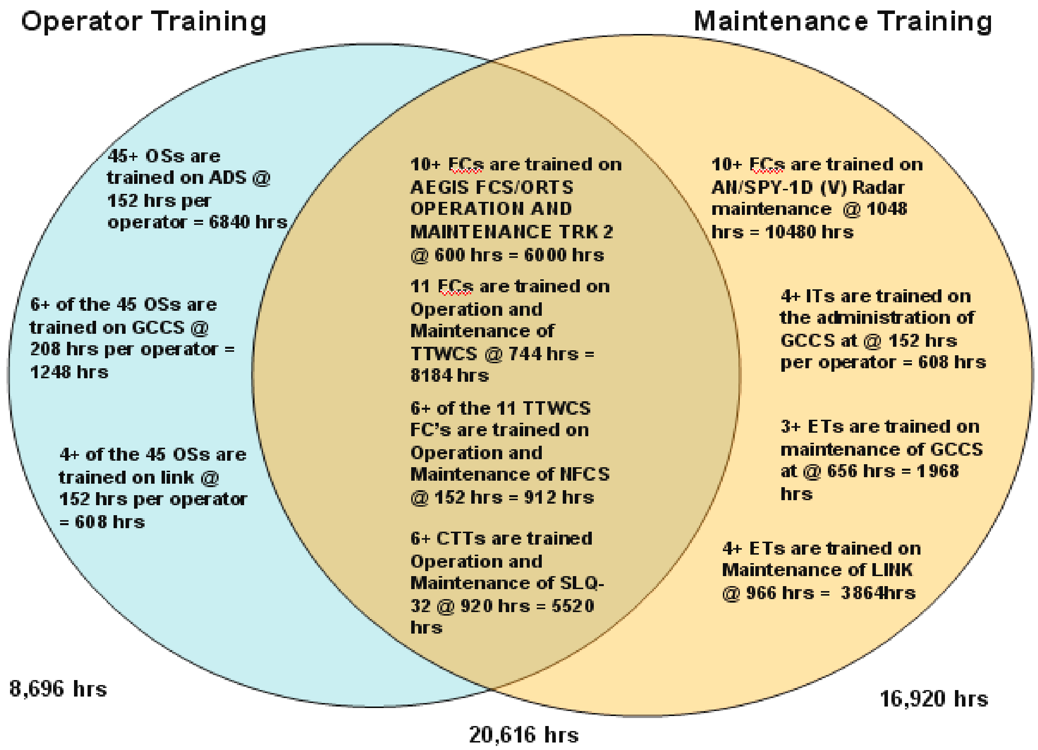


Figure 38. Operator and Maintenance Training Hours of C2 Systems

For the As-Is architecture, the operator, maintenance, and combined training sum up to over 45,000 training hours per Arleigh Burke-class DDG platform required for ADS, GCCS-M, C2P, TTWCS, NFCS, and SLQ-32.

The right side of Figure 38 includes the approximate manning requirements and training hours for those specific systems. System maintenance training hours sum up to over 16,000 hours of the course maintenance training.

Review of documentation enabled the identification of the number of hours associated with each system. This established a reference for total hours needed for each system. The primary challenge was to understand what parts of the curriculum covered similar functions between systems and how many hours were dedicated to each. The specific curriculum data needed to do this correlation was unavailable for some of the systems during this analysis.

Each system was designed and built to meet individual mission requirements. A review of each system's overlapping capabilities was accomplished. As the Venn diagram in Figure 39 illustrates, there are dedicated hours spent training similar

capabilities. For example, GCCS, ADS, and C2P provide geospatial displays and attempt to provide a visual representation of situational awareness. What could not be accounted for are the exact hours spent on those functions out of current system curriculum, but approximations could be made for a percentage of the course.

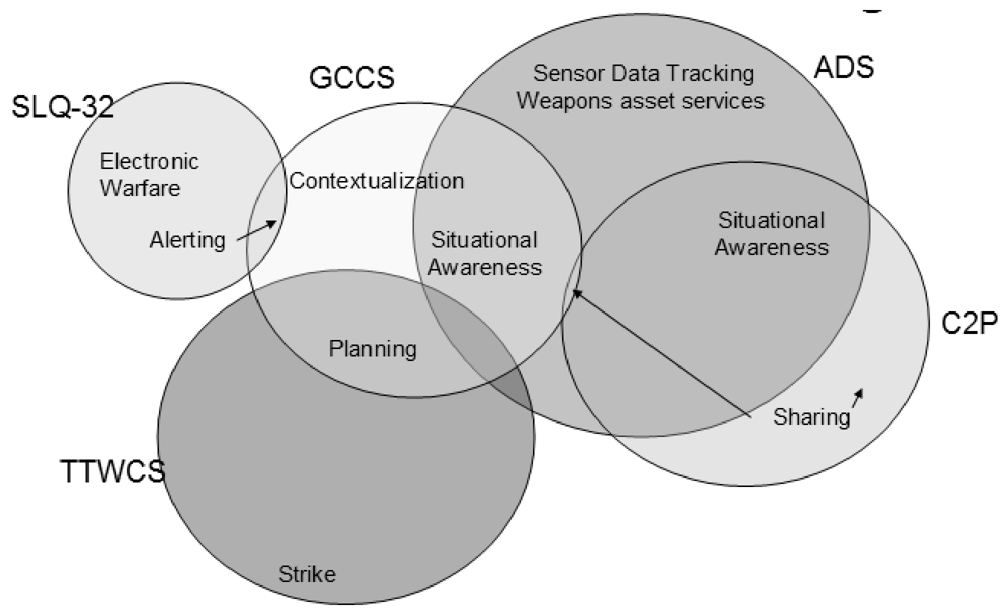


Figure 39. As-Is Operator Functional Element Overlap of Training

Training for the As-Is have some overlap in functional capability. This is a Venn diagram of the estimated amount of curriculum overlap for similar functional capabilities.

In the Hybrid architecture, there are potential savings on hours spent by reducing the overlaps. The Hybrid architecture incorporates reduction of training hours for operators because of the reduced number of display systems from many to two. As explained in the alternative description, the Hybrid is a migration towards a single visualization interface, which contains all needed functionality, and also includes a legacy system ADS. Further research shows some program offices are already placing importance in the investigation of saving time for system training and easing the workload of operators. For example, the program office for TTWCS has placed great emphasis on achieving common look and feel displays across multiple Land Attack Systems, i.e., ADS, GCCS-M, and NFCS [Sullivan and Mauser 2004]. Investments have been made into new alternatives through Office of Naval Research (ONR) funded research to allow separation of all TTWCS Human Computer Interaction (HCI) from the Weapon Control System applications. This would aid in the designing of human

interfaces around complete warfare tasks rather than individual operator functions. In doing so, the operator's view is expanded from looking through a "soda straw" to a "knowledge wall" [Sullivan and Mauser, 2004].

More than one program office may be investigating this approach in obtaining ways to ease the training time and workload challenges for operators. Potential training efficiencies that could be gained are represented in Figure 40. Some operator training hours would be reduced with a common display because of the reduction of functional overlap on a common display consoles in the CIC. For the Hybrid, the Aegis display functions would be maintained on the current consoles. The Hybrid would have some overlap and also include common visualization console covering the necessary functions of C2. There would be a framework that provides the common ontology, geospatial references, planning functions and provide standardized communications. All of the overlap between the various other systems would be covered in this common integrated display. Therefore all redundant functional elements are combined into a single training session. Specific mission unique capability packages could then be focused on providing more time dedicated to operator proficiency, instead of “buttonology” or “what the components of the interface are, what they do, [and] how to accomplish basic tasks.”

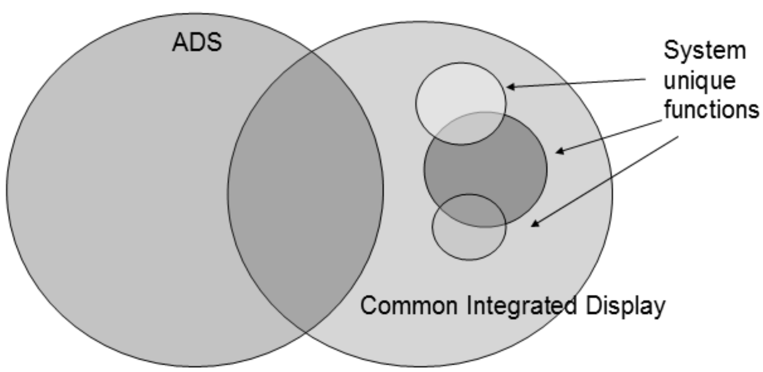


Figure 40. Hybrid Estimated Operator Training

Training for the Hybrid system includes the ADS display, the Common Integrated Display, and the unique functions.

Maintenance training hour’s reduction would only be recognized on the visualization aspect of the alternative; back-end aspects of each system would be

maintained. Because actual hours dedicated to a specific process could not be identified in the curriculum, estimations were made about overlapping training hours for the operator and maintenance courses. An approximation was made of a potential overlap reduction up to 30% while still allowing for specific mission unique capability training. For example, if this logic was applied to the hours outlined in Figure 38 (middle portion), roughly 20,616 hours could be reduced to 14,431 hours of training per platform.

For the GUN architecture, a single interface would be used, and operator training would include one common integrated display. The back-end systems would not be a part of this architecture as the information provided by these systems would be integrated into a data repository for subscription. Each operator would be trained on the system architecture as well as its functions, for example, how to access specific information of importance and how to tailor displays. Other system functions would include the setup for collaboration and sharing information with other participants.

Since the back-end systems would not be a part of this architecture, maintenance training hours would be reduced. Figure 41 depicts the reduced operator training for the GUN. The overall maintenance training hours would potentially decrease up to 50% to concentrate only on operation of this new system. Again, once trained on the basic framework, most training would focus on operational proficiency and specific unique operational capability instead of “buttonology” taking advantage of familiarity, common lexicon, and ontology.

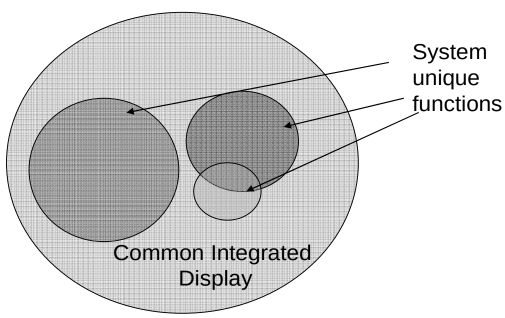


Figure 41. GUN Estimated Operator Training

Operator training for the GUN system includes training for the Common Integrated Display and the system’s unique functions.

The analysis performed in this section analyzed the last research question, "Does a unified C2 architecture reduce training costs?" This section focused on how the new architectures streamlined training. The Hybrid and GUN both reduced training hours. As a result, a unified architecture does have the potential to reduce the cost of training.

C. ARCHITECTURAL ANALYSIS RECOMMENDATIONS

The estimated performance from modeling was not as expected and did not show great variances between the alternatives. The models used did show that the GUN and Hybrid architectures both outperformed the As-Is architecture. The GUN architecture has received the overall highest utility score of 85.03%. The Hybrid architecture followed the GUN and received the second highest utility score of 84.84%. The As-Is has received the lowest utility score of 81.17%. These results are summarized in Table 12.

The cost efficiencies through training section showed how both the Hybrid and the GUN architectures required half the time for training operators and maintainers. This was demonstrated for an Arleigh Burke-class DDG as an example. In the example the 45,000 training hours needed to train maintainers and operators would be reduced to approximately 22,000. This time could be used in a multitude of ways. One recommendation is to use some of the saved time to train operators more generally on the art of C2 rather than system buttonology.

The overall utility scores of the GUN and the Hybrid architectures are very close and even though GUN is slightly higher, the scores are too close to make a distinction. However, GUN is believed to have many benefits that will be demonstrated upon further research. One of the reasons for this is because the GUN architecture utilized a loosely coupled services approach which could yield many life cycle benefits in the future. Also, remember the GUN will result in a 20% greater reduction in training than the Hybrid.

The GUN architecture is believed to grant the greatest long term benefits. It will on average reduce decision time by about three seconds to 52.6 seconds, reduce decision

error about four percent to 22%, increase the decision quality about three percent to 70%, and decrease training of operators and maintainers by 50%. It will also fulfill the U.S. Navy's desire to move towards a service-oriented architecture, making future upgrades easier. It is also expected, through prototyping and testing, the GUN will outperform the Hybrid in these areas. This is due to its more robust design, allowing for the data received to be collated and correlated more efficiently. It was also shown how the GUN and the Hybrid architectures achieve a reduction in training hours.

V. FINAL CONCLUSIONS

A. SUMMARY

U.S. Navy C2 decision-making quality, accuracy, and timeliness are being negatively impacted by the implementation of disparate systems that execute overlapping C2 functions. This development and deployment strategy has also resulted in high training costs. This report analyzes what C2 functions (focusing upon visualization support to sense-making) are currently employed at the surface combatant level and what, if any, unified visualization architectures could be defined. The analysis investigates if a unified architecture can improve the C2 measures of decision-making quality, accuracy, and timeliness while reducing training costs.

The following sections discuss the research questions addressed by this report and the results for each:

What are the functions of C2 at the surface combatant level? The Support Sensemaking function is the focus of this paper and is decomposed into Collate and Correlate, Provide Contextualization, and Share Information sub-functions. The visualization aspect of the Support Sensemaking function is analyzed as it relates to faster and higher quality decision making by generating alternative architectures and conducting modeling. Analysis provides definition and functions of C2 to remove ambiguity in the various definitions from different organizations. This paper clarifies C2 as the commander's ability to understand the situation, make timely decisions of the highest quality, and direct available resources in order to successfully execute a mission. Previous work done by Boyd and Brehmer is drawn upon in describing the decision making process loop. This research, along with U.S. Navy doctrine, provides the understanding necessary to decompose and synthesize the functions of C2.

What architectures can be defined that address common requirements of USN C2 decision-making, specifically related to visualization? Three feasible architectures are defined: (1) As-Is, (2) Hybrid, and (3) Global Understanding Network (GUN). The As-Is is the architecture currently deployed on surface combatants. The

Hybrid architecture concept takes feeds from the processing systems in the As-Is architecture and combines the information into a unified interface layer for use on common displays while also maintaining some legacy interfaces. The GUN architecture concept accepts all of the data sources of the As-Is architecture and makes all information available on each operator's display in a unified visualization architecture.

Can decision-making quality, accuracy, and timeliness be quantified and modeled within unified C2 architectures? Feasible alternatives are evaluated through simulations and show a decrease in average decision time and average decision error when comparing the As-Is to the alternatives where fewer displays are used. An increase in average decision quality is indicated in the same comparisons. A swing weight technique is used to determine how the changes in the values of the attributes are important to the stakeholders and provides additional relevance to the raw data. The resulting order of preference is the GUN followed closely by Hybrid. Both solutions are preferred over the As-Is.

Does a unified C2 architecture improve decision quality, accuracy, and timeliness? The GUN model decreased the average decision making time to 52.78 seconds with a measured improvement of 5.6% (3.12 seconds) over the As-Is. The probability of decision error is decreased to 0.4163 with a measured improvement of 20% (0.2026). Quality of decision is increased to over 70% with a measured improvement of 2.9%. These improvements are considered significant in time critical scenarios (less than 90 seconds to make a decision) such as Cruise Missile Defense or Search and Rescue. Other missions not requiring this level of time critical evaluation do not contribute or validate this data and may need more fidelity in the model and simulations.

Does a unified C2 architecture reduce training costs? The analysis estimates training overlap for the Hybrid could be reduced as much as 30% and for the GUN up to 50% compared to the As-Is. Navy manpower and training documentation is evaluated to identify if a unified C2 architecture reduces training costs. Total student hours for a sample of the disparate C2 systems are tallied. Training time spent on the functions of C2 per system could not be ascertained, however, analysis of each of the system

capabilities uncovered overlaps. The alternatives demonstrate a reduction in capability overlaps, and as a result, infer a lower amount of hours needed to train. We believe this is a direct result of the newer alternatives introducing a common integrated display, and a C2 functionality framework providing common ontology and increase familiarity. It is expected that if all core functionality could be taught once, then only mission specific capability and decision aids need to be addressed during training.

B. CONCLUSIONS

The estimated performance from modeling did not show significant distinction between the GUN and Hybrid alternatives although, both performed significantly better than the As-Is architecture. The overall utility scores of the GUN and the Hybrid architectures are very close and even though GUN is slightly higher, the scores are too close to make a distinction. However, GUN is believed to have many benefits that will be demonstrated upon further research and is believed to grant the greatest long-term benefits. The GUN concept could also fulfill the U.S. Navy's desire to move towards a service-oriented architecture, making future upgrades easier. The cost efficiencies through training reduction revealed the Hybrid and the GUN architectures requiring half the time for training operators and maintainers, which add to the benefits of these architectures.

C. AREAS FOR FUTURE STUDY

The Hybrid and the GUN architecture concepts proposed both indicate merits in performance over existing architectures. This report, however, only investigated a small subset of C2 functionality (visualization in support of sense-making). Expanding the functional analysis to include Collect Information, Command, and Plan will further vet the alternative architectures. Further development of the modeling and simulation of the alternatives, by the addition of cognitive reasoning and data recognition, may provide a more definitive choice. A full Life Cycle Cost Estimate should be performed on the Hybrid and the GUN to enable a thorough quantitative cost-benefit analysis along with a

Manpower Reduction Study (MRS). Using the results of the LCCE, MRS, and refined modeling and simulation, a determination can be made to develop either the Hybrid or the GUN. Provided the LCCE does not yield exceptionally high costs for this project, development of a prototype of the best candidate alternative to verify the modeling and simulation could proceed.

APPENDIX A: PROJECT PLAN

1. INTRODUCTION

1.1. PROJECT DESCRIPTION

1.1.1. Problem Statement

The Navy's Command and Control (C2) strategy does not have a common set of C2 requirements that can be used across multiple surface ship platforms. There is a need to define a common set of C2 requirements to support the creation of a common enterprise level C2 architecture while considering emerging service-oriented architecture technologies. Two approaches considered to building this set of requirements are: defining a superset of requirements that can be pulled from to support a platform's ability to accomplish a specific mission, and establishing the core set of requirements common among all platforms that can be built on. Either approach would define the subset of requirements that is common for surface ship C2 requirements. The benefit of having a defined subset of requirements would simplify the DoD acquisition process by minimizing the work needed for requirements' definition for new platforms. This would lay the groundwork for a common fundamental architecture. It will also yield cost savings with reduced research and development requirements' definition, analysis, performance based mission thread analysis, and operations training and support.

1.1.2. Bounded Problem Statement

The Navy has many different platforms, each of which makes use of a variety of weapons and sensors. Ideally all of the Navy's platforms will have a common C2 framework. This project will concentrate on the C2 architecture of surface combatants including DDGs, CGs, and FFGs (destroyers, cruisers, and frigates). Surface combatants provide a wide range of capabilities and participate in group operations including Carrier Strike Groups (CSGs), Expeditionary Strike Groups (ESGs), and Surface Action Groups (SAGs). Two types of missions will be analyzed: a combat mission and a non-fire mission. The first mission thread to be analyzed will be surface ship air defense. The second mission thread will focus on a typical search and rescue mission. These missions range from man over board to answering the distress call of a damaged ship. The assumption is defining a universal set of C2 requirements will be aided by choosing two mission threads that greatly differ in scope.

1.1.3. Project Goal

The goal of this project is to develop a comprehensive listing of command and control requirements and proposed architecture for surface combatants which fit the mission threads. This will provide a descriptive scenario for a usable C2 sample set available to navy ships. Systems engineering analysis will examine this information to identify and develop a common set of C2 features that should be utilized for all future surface ship acquisitions. The normative scenario, the project goal, will be a bundled package of C2 features required for all ships.

1.1.4. Value Added

The benefits of having a universal set of requirements include a simplified DoD acquisition process, decreased program cost, greater interoperability, accurate and intuitive communication. These benefits come from the fact that our project will streamline the requirements' definition of many Navy platforms, and increase the Navy's performance. This project will apply modern systems engineering processes to analyze C2 requirements on a subset of US Navy ships performing critical missions.

1.2. RISK MANAGEMENT PROCESS

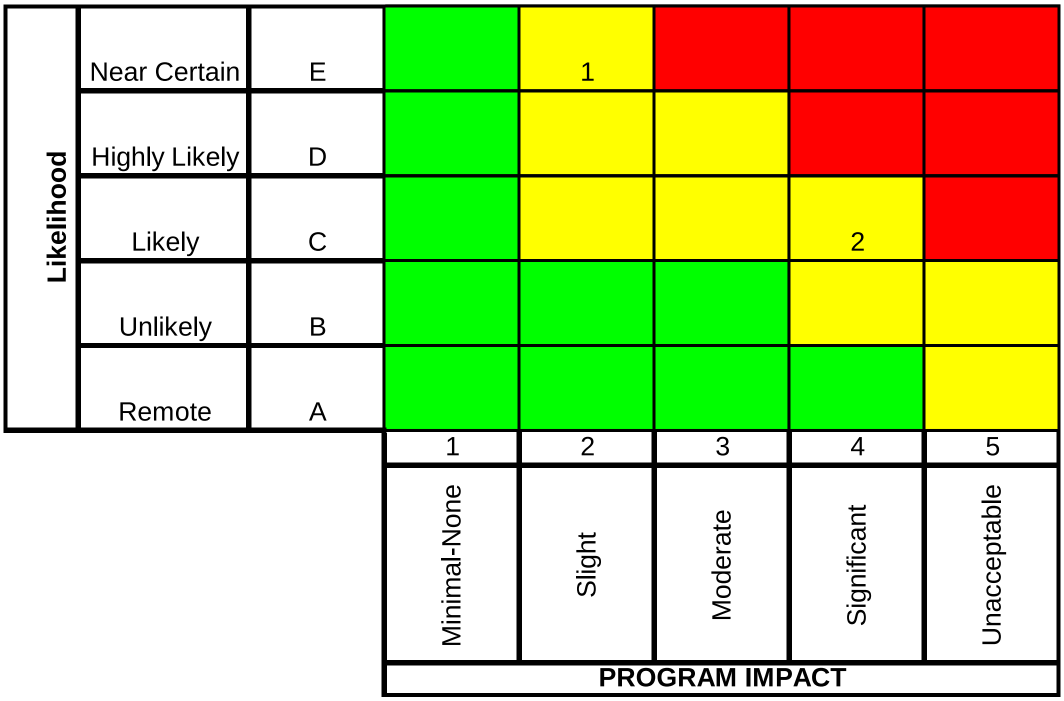
1.2.1. Risk Management

A modified and abbreviated version of the DoD Risk management process outlined in the *"Risk Management Guide for DoD Acquisition"* will be utilized to deal with and analyze risk. Risk will be identified and tracked. Risk drivers will be identified, and risk mitigation strategies will be developed. All of this will be done continually throughout the project's life cycle.

The risks will be documented and tracked through a Risk Table and a Risk Matrix. In this approach, there are two basic risk components that will be used for every risk event. The first is the *Likelihood* that the risk will occur. The second is the severity of the *Impact* if that event happens.

1.2.2. Current Risks and Status

Our Project Management Team has already identified two risks. These risks are listed in the matrix and table below. The status of these risks will be presented to all stakeholders during Interim Progress Reviews (IPRs) and upon request.


Likelihood
Near Certain
E
Highly Likely
D
Likely
C
Unlikely
B
Remote
A
1
2
1
2
3
4
5
Minimal-None
Slight
Moderate
Significant
Unacceptable
PROGRAM IMPACT

ID	Name	Description	Assigned	Status	Likelihood	Impact	Overall Risk
1	Group Locations	Geographic Locations between Philadelphia and San Diego. Scheduling times has been difficult due to the three hour time difference and site locations	Project Management Team	Monitoring	E, Near Certain	2, Slight	Yellow
2	Project Schedule	Being able to stick to the Schedule that NPS has laid out for CAPSTONE project. Meeting all the deliverable dates for this project. May need to scale down on scope if schedule risk is elevated to red.	Project Management Team	Monitoring	C, Likely	4, Significant	Yellow

Table 11: Risk Tracking Table

1.3. ORGANIZATIONAL STRUCTURE

Figure 1 shows the organizational structure of the team. The structure is broken up by physical location with a lead assigned for each location. Some of the members have been assigned specific tasks; however, this does not imply they will not be helping with other tasks. John Waxler has been assigned the overall lead due to the fact that Philadelphia is the larger site and this will allow him to meet face to face with the majority of the team members.

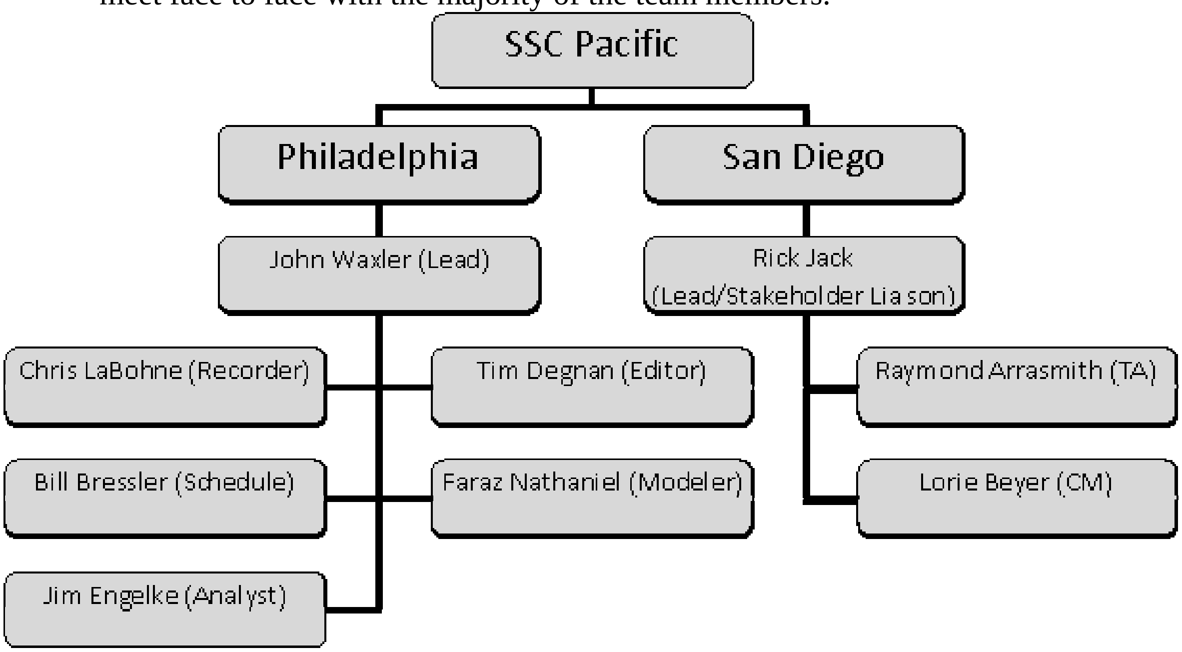


Figure 1: Organizational Structure Diagram

The following describes the responsibilities of each team role. The Leads will be responsible for ensuring the work is fairly distributed and encouraging people to attend meetings and stay on top of their work. The Recorder will be responsible for meeting minutes. The Editor will be responsible for formatting and submitting deliverables. The Scheduler will be responsible for ensuring the schedule is followed along with updating changes in the schedule and adding granularity as deadlines become closer. The Modeler will ensure all modeling is done correctly and lead the modeling effort. The Analyst will perform reviews of work along with aid in all aspects of the process. The Stakeholder Liaison will

leverage real world contacts in order to get stakeholder input in a variety of areas of interest. The TA will be responsible for maintaining our section of blackboard. CM (Configuration Management) will be responsible for ensuring team follows good CM practices such as revision tracking and archiving. Many members of the team will have their hands in many parts of these roles and more, however, they will take accountability for the roles named in the above chart.

2. SYSTEM ENGINEERING APPROACH

2.1. OVERVIEW

The System Engineering Design Process (SEDP) method uses an iterative design approach composed of three phases: Problem Definition, Design and Analysis, and Decision Making. It will be the primary tool used to define the C2 requirements and desired architectural baseline the Navy needs. An examination of the waterfall, classic Vee, and spiral system engineering processes was conducted to determine the best approach for this problem (Blanchard and Fabrycky, 2006, p. 30). It was determined a modified SEDP process (Figure 2) derived from a combination of Sage & Armstrong's life cycle of system engineering and the US Military Academy system engineering approach as taught by the Naval Postgraduate school is the best approach (Sage and Armstrong, 2000).

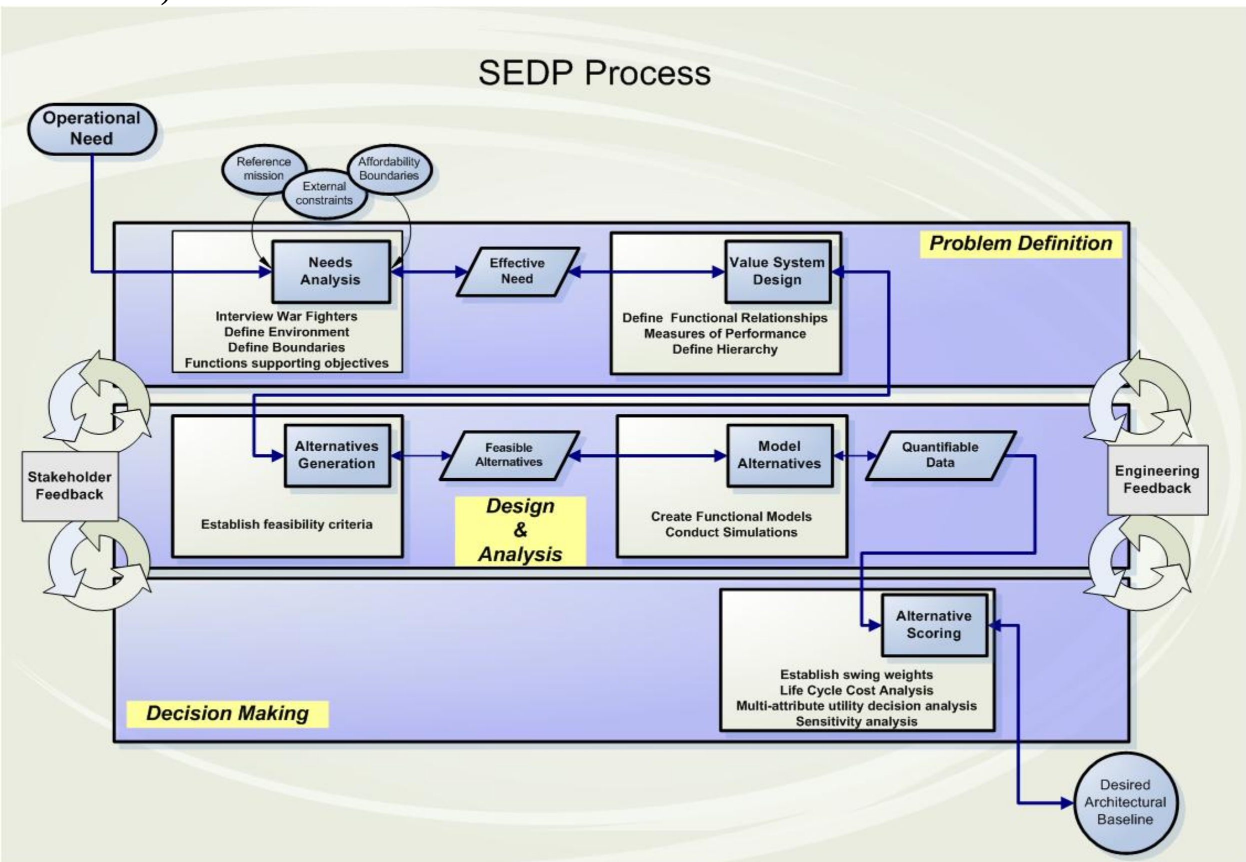


Figure 2: SEDP Diagram

During the Problem Definition phase of SEDP, in-depth research and extensive analysis of C2 concepts is conducted. The Needs Analysis defines the environment, boundaries, and objectives. Stakeholders are identified and interviewed to refine requirements and produce an effective need. The effective need is used to guide the identification and examination of various components needed to accomplish the task and establish metrics to measure successful completion of the task. A value system design will define functional relationships, hierarchy, and initial measures of performance used in the next phase.

In the Design and Analysis phase, various alternatives are created with the ability to meet the effective need and perform within the desired thresholds. After considering various system requirements and project constraints, the alternatives are considered for feasibility. Qualitative and quantitative modeling and simulation is used to assess the complexity and performance of the alternatives. The metrics used in the modeling generate a raw data matrix, and are used in the Decision Making phase.

In the Decision Making phase, a scoring criterion is solicited from the customers that assists in transforming the raw data into information used in the decision process. Methods for this include the Multi-Attribute Utility Theory (MAUT), Swing Weight Technique, and Sensitivity Analysis. These methods generate total value scores for each alternative. Estimated costs for procurement are considered with the utility scores as part of an assessment of Cost vs. Total Value.

2.2. PROBLEM DEFINITION PHASE

2.2.1. Needs Analysis

In the first phase of the SEDP a Needs Analysis is performed. Stakeholders are interviewed in order to articulate the operational need in such a way as to fully understand the problem. This will help identify if the problem is based upon a mission thread or sets of mission threads that have external constraints such as doctrinal, environmental, and geo-political. The Needs Analysis will take into account the integrated architecture with Doctrine/ Organization/ Training/ Materiel/ Leadership/ Personnel/ Facility (DOTMLPF) information and provide a structured and organized approach for defining capabilities and understanding the underlying requirements for achieving those capabilities (Chairman of the Joint Chiefs of Staff Instruction 3170.01F, 2007). While conducting the Needs Analysis, affordability boundaries are identified and taken into account. The team will utilize tools that enable an efficient approach to this problem, such as the development of use cases and conducting stakeholder analysis. The output of the Needs Analysis will be a detailed set of requirements and the articulation of the problem's effective need. To ensure requirements are tracked and analyzed we will employ the use of traceability tools such as CORE. Because of geographic differences between the groups, we may employ a web based tool like the Requirements Collection,

Analysis, and Management (RCAM) developed by Space and Naval Warfare (SPAWAR) Systems Center for collaboration purposes.

2.2.1.1. Stake Holder Analysis

Three fundamental organizations will gain from the C2 architectural baseline description produced from this project. They can be grouped into those who pay for the architecture, the resource community; those who buy the architecture, the acquisition community; and those who use the architecture, the war fighter community. The team will work as a liaison between the three groups for the development of the baseline requirements and architectural delineation. Any disagreement between organizations will be handled by a forum, which will allow adjudication enabling each vested member to vote. Adjudication of issues will follow a process similar to the NAVAL NETWAR/FORCEnet ENTERPRISE Board of Directors (NNFE BoD) where representative members from each community will make a decision as a group to move forward.

2.2.1.2. Resource Community

The resource sponsor group is responsible for an identifiable collection of resources which comprise inputs to warfare and supporting warfare tasks by planning and identifying the funding for the requirements. A common set of C2 requirements provides a potential savings in R&D by reducing individual specific C2 architecture designs. For this task a representative from the Office of the Chief of Naval Operations (OPNAV) will be heavily consulted.

- OPNAV N6F2 – Department of the Navy, Chief of Naval Operations Communication Networks

- OPNAV N86 – Department of the Navy, Chief of Naval Operations Warfare Integration, Surface Warfare Branch.

2.2.1.3. Acquisition Community

The execution agents and systems commands would be responsible for the development and acquisition of the architectural baseline and supporting them once fielded. For this task the team will use representatives from the Program Executive Offices (PEO) and Systems Commands. This may include:

- Program Executive Office, Integrated Warfare Systems-5

- Program Executive Office, C4I

    - PMW760 Surface Combatant Integration

- Chief of Naval Research

    - Ship Systems and Engineering Research Division (Code 331)
    - C4ISR Applications (Code 313)
- Space and Naval Warfare Systems Command
    - 5.0 Engineering Division

2.2.1.4. War Fighting Community

The War Fighting community drives the requirements for the common C2 architecture. Their tactical and operational experience is essential in providing data for this architecture. This in turn provides benefit back to the war fighter to enhance the mission execution. For this task the team will use representatives from the fleet. This may include:

- U.S. Fleet Forces Command
- Naval Network Warfare Command N6-N8
- Expert opinion from Fleet commander representatives

2.2.2. Value System Design

The second logical step in the SEDP is the Value System Design. The Value System Design will start with defining objectives and organizing them in an objectives tree. The types of objectives useful for a C2 Architecture are compatibility, performance, reliability, quality, adaptability, cost, and flexibility. Types of objectives not being considered include profit, market, and competition based objectives (Blanchard and Fabrycky, 2006). Each of the objectives defined are given an objective measure. These objective measures are used in evaluating the effectiveness of alternative courses of action and ultimately measuring success or failure of the C2 architecture design.

2.3. DESIGN AND ANALYSIS PHASE

2.3.1. Alternatives Generation

Using the defined objectives from the Value System Design, research is conducted to determine if solutions or partial solutions exist. If not, further research is conducted to determine feasibility of development for identified gaps. Candidate architectures will be analyzed using selected tools such as trade studies to determine those that are feasible and those that are not considered feasible based upon the objectives. Whole candidate alternatives will be considered and selected for further analysis and is used in the modeling step.

2.3.2. Model Alternative

Alternatives that are determined feasible will be illustrated using models determined to be practical for modeling a notional high-level C2 architecture. Functions defined in the Needs Analysis are included in models such as IDEF0 and Functional Flow Block Diagram (FFBD) and will show the resulting functional flow. Simulations will be run using COREsim and Excel as necessary to aid in the decision making process. Upon completion the team should have quantifiable data that can be used in the decision making phase.

2.4. DECISION MAKING PHASE

2.4.1. Alternative Scoring

The alternatives will be ranked based on an assigned score. The score will be determined by taking the raw scores for each objective and its measure obtained in the analysis phase and converting them into a utility score. Methods for this include the Multi-Attribute Utility Theory (MAUT), Swing Weight Technique, and Sensitivity Analysis.

2.4.2. Desired Architectural Baseline

A presentation of alternatives with the respective derived score will be given to the stakeholders for the final selection of the set of requirements and the C2 architecture. The alternative with the highest score is considered to meet the defined objectives best and is therefore the recommended solution; however the final decision rests solely with the stakeholders. Additional considerations for each alternative to aid the stakeholders' decision are presented with the scores and include: limiting and strategic factors, independent criteria, cost, and risk (Blanchard and Fabrycky, 2006).

3. DELIVERABLES & SCHEDULE

3.1. DELIVERABLES

The following are the deliverables for the Capstone Project.
Quarter #6:

- Initial Capstone Project Report and Brief will be presented at ***Interim*** Progress Review one (IPR #1) at the end of the quarter December 2008 and will focus on:
    - Project Management Plan
    - Stakeholder Analysis
    - Needs Analysis
    - Effective Need Statement

    - Functional Analysis
    - Measures of Performance
    - Hierarchical Design

Quarter #7:

- An updated Capstone Project Report and Brief will be presented at IPR #2 in March 2009 and will focus on:
    - Alternatives Generation
    - Establish Feasible Alternatives
    - Create Functional Models
    - Conduct Simulations
    - Define Quantifiable Data

Quarter #8:

- A Final Capstone Project Report and Brief will be presented in June 2009
    - Establish Swing Weights
    - Multi-Attribute Utility Decision Analysis
    - Sensitivity Analysis

3.2. SCHEDULE

This Project spans three academic quarters. A high level schedule is provided in Figure 3. It shows the deliverables and milestones for the Capstone Project.

- Approval of PMP
- PRR #1
- IPR #2
- Final report and brief

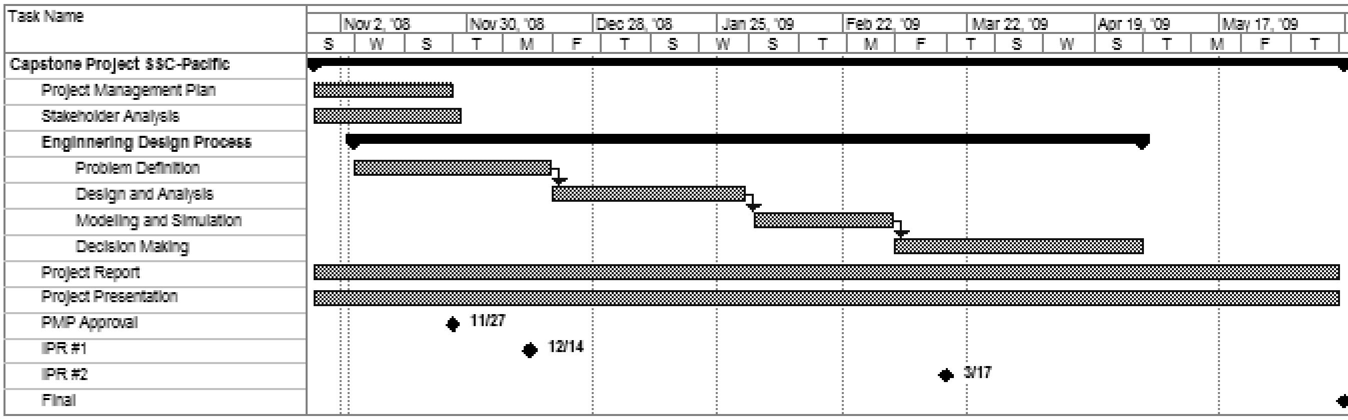


Figure 3: Project Schedule

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APPENDIX B: ZWICKY'S MORPHOLOGICAL BOX

System Functions: Support Sensemaking		
Collate and Correlate	**Provide Contextualization**	**Share Information**
Human	Human	Human
Yellow Sticky's	Paper Map	Paper
White Board	Chess Board(physical rep)	Website
3 Ring Binder	White Board(Drawing)	COTS Digital sharing system
Fuzzy Logic engine	COTS Digital Context system	GOTS/COTS Mixed sharing
COTS Database	GOTS/COTS Mixed Context system	GOTS Militarized sharing
Data Correlation engine	GOTS Militarized Solution Context system	Real-time Data Distribution Service
GOTS Militarized	Hologram	
Web Mash-ups	Mixed Legacy (ADS) and New Standardized and Customizable Visualization	
Service Adapter		
Pre-Cogs	Virtual Map	
Mind links	Halo Deck	Mind Links
Shared Knowledge	Shared Knowledge	Shared Mental states
Halo Deck	New Standardized and Customizable Visualization	Updated to share new data
Quantum Computing		
Unique Interface Correlation Server (UICS)	Remote Display System	Radio Telephone
Common Computing Correlates	MIDB	SATCOM
	Audible alerts	LINK 16
	Visual alerts	Semaphore
	TDBM	Light based Semaphore
	AEGIS	Nautical Flag
	Visualization Correlator	OPNOTE
	Cross Domain Solutions	Commander's Intentions
	NGA products	1MC
	Data Fusion	General Quarters
	Joint Mapping TookKit	Computer based exchange
	Google Earth	USMTF
	ESRI ARCView	EMAIL
	Microsoft Virtual Earth	Website
	MIL-STD 2525	CEC
	OpenGIS symbology	TADIL
	NTDS symbology	
	FalconView	
	OpenMap	

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APPENDIX C: INTERVIEW QUESTIONNAIRE

Problem Statement

The Navy's Command and Control (C2) strategy does not have a common set of C2 requirements that can be used across multiple surface ship platforms.
There is a need to define a common set of C2 requirements to support the creation of a common enterprise level C2 architecture while considering emerging service-oriented architecture technologies. Two approaches considered to building this set of requirements are: defining a superset of requirements that can be pulled from to support a platform's ability to accomplish a specific operation and the core set of requirements common among all platforms that can be built on. Either approach would define the subset of requirements that is common for surface ship C2 requirements.

Scoping and Bounding:

We will concentrate on only surface combatants (FFG, CG, DDG, DDX, CGX)

To keep focused, we will apply 2 mission threads to this particular problem:

Area Missile Defense
Search and Rescue

1. From your community's perspective, what are the benefits of a common set of requirements and a common C2 architecture aboard surface combatants?

2. There are many definitions of C2, the Department of Defense (DoD) [1] defines *command and control* as follows.

    - The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing,

coordinating, and controlling forces and operations in the accomplishment of the mission.

But in order to create an architecture and form requirements we needed to understand what the functions of C2 are and establish a way to apply this to different mission threads. If we recognize that C2 must be understood from an organizational perspective and as such it refers in general to the means through which an entity (e.g., a military organization) functions in the world. We attempt to define C2 using the old definition and newer concepts to state:

Command and control is the process and structures through which a unit operates. The units are made up of components, and how these components function with regard to planning, directing, coordinating, and controlling the accomplishment of combat and other mission is C2.

We will attempt to outline and architect this process and determine how the various components will function from the mission thread perspective.

Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree ☐

Thoughts?

3. Do you see any weaknesses in pursuing an architecture based on a common set of requirements?

4. Would automation be needed and if so which part of the process?

5. What information do you see as most important to C2?

6. Is there data that is desired that is not readily available today?

7. For missile defense:
8. For Search and Rescue:

9. What areas of C2 do you see as needing the most improvements?

Due to time constraints on this project we have attempted to come up with assumption that would also help bound the problem.

Do you agree with these assumptions?

- Assumptions

  Yes ☐ No ☐ All architecture work will be on the unclassified level

  Yes ☐ No ☐ Threats should be typical of current technology.

  Yes ☐ No ☐ The system does not need to encompass all aspects of C2. (It should include at least the common ones.)

  Some ideas of what we consider external to the system (meaning we are not asking to be paid for or designed as part of the system)

  Yes ☐ No ☐ National Assets

  Yes ☐ No ☐ Sensors

  Yes ☐ No ☐ Engagement elements (Fire control Radars, Weapons, Aircraft, etc.)

  Yes ☐ No ☐ We work within the existing military organizational hierarchal structures (not creating our own, or proposing new structure or doctrine for chain of command)

  Yes ☐ No ☐ We will be concentrating on North Korean cruise missile threats

Yes ☐ No ☐ Our SAR is going to be a downed aircraft.

- This is not a Special Forces operation. This is an international water US aircraft down scenario.

Do you have any recommendation for change?

APPENDIX D: LIST OF MOE/MOPs

- **A2 Sensemaking**
    - OBJ: Provide a concise and accurate operational assessment which expedites accurate Decision Making.
        - MOE: Quality of Picture (Time Decision Making Takes). This measures the overall sensemaking assessment.
        - MOP: Average change in seconds between Decision making with old Sensemaking output and modified output. This measures the time change between the old sensemaking assessments versus the improved or changed sensemaking assessment.
    - OBJ: Perform Sensemaking at least as quickly as it is currently being executed.
        - MOE: Time of Sensemaking process. This measure provides the overall time decision making takes for sensemaking
        - MOP: Average Change in seconds between old Sensemaking process and modified process. This measure captures the time delta between the legacy sensemaking processes versus the improved or changed sensemaking process.
- ***Collate and Correlate (A21):*** This function collects and organizes the information for processing by the system.
    - OBJ: Organize your mission relevant information and make logical relationships between data.
    - *A211 Organize Information (Collate):* This sub-function starts the process of sorting out all of the provide information that contributing C2 systems provide. This sub-function determines if the collected information is relevant to the mission and rejects non-mission essential information. Once complete the filtered information is made available for correlation.

- A211 MOE: Ability to provide Clear and concise data: This measure provides the ability to concentrate on mission data.
- A211 MOP 1: % Redundancy properly identified: Capturing this data point provides a means of making sure the data collected has not already been provided. When done correctly this MOP will save the user time from going through already provided data that has not changed from original submission..
- A211 MOP 2: % conflicting properly highlighted: When information is gathered it is important to show any information that contradicts other information. This is important because contradicting data should be examined closely to determine the accuracy of the systems providing that data if they are evaluating the same area of interest.

- *A212 Link Related Items (Correlate):* This sub-function provides that ability for the user to make logical relationships between data and information being provided by the C2 systems. These relationships will be needed to provide a better understanding of the area of interest.
  - A212 MOE: Ability to identify meaningful relationships: This measure captures how well the system is actually identifying relationships that are needed for the mission.
  - A212 MOP 1: % Type I errors: This measures the ability to filter out false positive information. This measure is critical because it determines the accuracy of the system for information that was once deemed important but the system filtered it out because it did not make sense given the specified mission criteria.
  - A212 MOP 2: % Type II errors: This measures the ability to measure false negative information. This measures the ability of the system to look at information that was originally classified as non important but reexamined it now seems relevant in the given mission.

- ***Provide Contextualization (A22):*** This function puts the information in context and displays the information.
    - *A221 Establish Knowledge of Battle Space*: This sub-function is the beginning of creating the area of interest or battlespace.
        - A2211 Analyze Historical Information: In this sub-function any historical information is provided for the mission,
            - A2211 MOE: Enhance Operational Assessment based on Historical Information: This measures the way the current mission information is assisted by using historical data.
            - A2211 MOP: Accuracy of assumptions made based on this information (Adjustment made that was correct/Total Adjustments): these measures determine if the historical data aided in the decision making process.
            - A2211 MOP: How many minutes-hours does it take to analyze: This data point capture the length of time it takes to analyze the historical data related to the mission.
        - A2212 Analyze Intelligence: In this sub-function intelligent data is further analyzed for completeness.
            - A2212 MOE: Enhance Operational Assessment based on Intelligence Data: This measure captures that ability to incorporate the intelligence data and applying it the mission.
            - A2212 MOP: Accuracy of assumptions made based on this information (Adjustment made that was correct/Total Adjustments): This measure determines if the intelligence data aided in the decision making process.
            - A2212 MOP: How many minutes-hours does it take to analyze: This data point captures the length of time it takes to analyze the intelligence data related to the mission.

- *A2213 Analyze Environmental Data:* Provides the weather: terrain: lunar/solar: ocean conditions and other environmental factors related to the mission.
    - A2213 MOE: Enhance Operational Assessment based on Environmental Data: This measure captures that ability to incorporate the environmental data and applying it the mission.
    - A2213 MOP: Accuracy of assumptions made based on this information (Adjustment made that was correct/Total Adjustments): This measure determines if the environmental data aided in the decision making process.
    - A2213 MOP: How many minutes-hours does it take to analyze: This data point capture the length of time it takes to analyze the environmental data related to the mission.
- *A2214 Establish Mission Specific Associations as a whole:* This sub-function takes all the related information and filters out relationships that are not applicable to the mission.
    - A2214 MOE: Establish relationship between disparate data points: This measures the ability to relate seemingly un relatable data in a logical manner.
    - A2214 MOP: Ratio of actual events that are related: Measuring how accurate the information that is presented as being related actually is related for a given mission.
- *A2215 Monitor New Mission Specific information:* Tracking real time or near real time data that may be useful to the mission.
    - A2215 MOE: Enhance Operational Assessment based on New Data: Measure the accuracy of tracking new data that relates to the mission.
    - A2215 MOP: Accuracy of new assumptions made (Adjustment made that was correct/Total Adjustments):

This measure determines if the new mission specific information data aided in the decision making process.

- A2215 MOP: How many seconds does it take to make the adjustments: This data point capture the length of time it takes to analyze the new mission specific information data related to the mission.

- ***A222 Provide Common Visualization:*** This function provides the common visual display no matter which C2 system is providing the information.
  - A222 OBJ: The common visualization should have customizable views allowing the operator to focus on a specific location, time, and set of data.
    - *A2221 Tailor Display:* This sub-function allows the data to be displayed in a manner based on user preference.
      - A2221 MOE: Configure to display only relevant info based upon user set criteria: This measure captures the ability for the user to manipulate the display feature to assist in viewing the information provide related to the mission.
      - A2221 MOP 1: Average time to display relevant info in seconds: This measures how fast a manipulated display can provide the visual information.
      - A2221 MOP 2: Average perception of Tactical picture quality: Through the use of surveys provided to the user, feedback is captured with respect to the display features.
    - *A2222 Provide Geospatial Reference:* This provides a geographical reference a visual mission rehearsal.

        - A2222 MOE: Establish orientation: This measure determines if the geospatial reference is true.
        - A2222 MOP: Mean Accuracy of positional orientation: This measures how accurate the geospatial reference is with respect to missions.
    - *A2223 Provide Standard Ontology for Information (Symbology):* This allows for all the users to understand anything that is displayed using a common symbol no matter which C2 system provides the information.
        - A2223 MOE: Establish standard information presentation: This measures how effective standardizes information.
        - A2223 MOP: % of information displayed using proper standard: They capture the accuracy of how the standards are used. Are they used correctly, are they provided correctly from the C2 system and from the user.
  - ***A223 Alert on Pattern or Anomaly:*** This function will track and alert to any changes to mission parameters.
    - A223 MOE: Generate alerts based upon pattern change for a set mission parameter: This measure captures the system alerts that are triggered by changes to a set of mission criteria.
    - A223 MOP: Number of false alarms: This captures how accurate the function is with false alerts.
- ***Share Information (A23):*** This function allows for mission data and information to be shared to other C2 systems.
  - A23 OBJ: Provide shared situational awareness by integrating information from various sources (sensors, emitters, reporting networks, plans, orders, etc.).

- *A231 Collaborate with Participants:* This sub-function captures the ability to share information between mission participants.
    - A231 MOE: Ability to share missions: This measure captures the accessibility of shared mission data.
        - A231 MOP 1: Percent of intended recipients informed: This measures the success rate to share mission data.
        - A231 MOP 2: Number of unintended groups informed: This measures the success rate to not provide mission data to users that do not have authorized access.
        - A231 MOE: Ability to share missions in near real time: This measures the ability to share real time data to participating mission users
        - A231 MOP: Measured in seconds: This measures how quicklyreal time data can be sent and shared to mission participants.
- ***A232 Establish Authoritative R2:*** This function sets the reporting responsibility.
    - A232 MOE: Ability to recognize decision hierarchy: This measures the ability for the mission approval cycle to be escalated to the final decision maker.
    - A232 MOP: Percent informed: This measures the total participants informed of the mission decision hierarchy.
- ***A233 Communicate Standardized information***: This sub-function provides a communication method to provide standardize information.
    - A233 MOE: Ability to distribute standardized information: This measures the ability to send standardize mission information.
    - A233 MOP 1: Average Number of orders issued: This measures the overall average of mission orders delivered to the intended recipient.

- A233 MOP 2: Percent messages displayed inaccurately: This measures if the message was delivered correctly.

APPENDIX E: ACRONYM LIST

Acronym	**Term**
ADS	AEGIS Display System
AIS	Automatic Identification System
A_O	Operational Availability
AOR	Area Of Responsibility
C2	Command and Control
C2UniArch	Command and Control Unified Architecture
C2P	Command and Control Processor
CANTRAC	Catalog of Naval Training Courses
CCRP	Command and Control Research Program
CDC	Combat Direction Center
CG	Guided Missile Cruiser
CIC	Combat Information Center
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
COA	Course of Action
COP	Common Operational Picture
CSG	Carrier Strike Group
DDG	Guided Missile Destroyer
CMD	Cruise Missile Defense
DIACAP	DoD Information Technology Security Certification and Accreditation Process
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DoD JCS	Department of Defense Joint Chiefs of Staff
DOODA	Dynamic Observe-Orient-Decide-Act
EFFBD	Enhanced Functional Flow Block Diagram
EMI	Electro-magnetic Interference
ESG	Expeditionary Strike Group
FFBD	Functional Flow Block Diagram
FFG	Guided Missile Frigate
GCCS-M	Global Command and Control System Maritime
GT	Gross Tonnage
GUN	Global Understanding Network
HCI	Human Computer Interface

IA	Information Assurance
IAW	In Accordance With
IDEF	Integration Definition for Function Modeling
IP	Interface Processor
ITS	Information Technology System
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chiefs of Staffs
JFMCC	Joint Force Maritime Component Commander
JICO	Joint Information Control Officers
JP	Joint Publication
LCCE	Life Cycle Cost Estimates
M&S	Modeling and Simulation
MDA	Maritime Domain Awareness
MIL-STD	Military Standard
MLDT	Mean Logistics Delay Time
MMT	Mean Maintenance Time
MOC	Maritime Operations Center
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSSE	Master of Science in Systems Engineering
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
NFCS	Naval Fires Control System
NNWC	Naval Net Warfare Command
NSS	National Security System
ONR	Office Of Naval Research
OODA	Observe-Orient-Decide-Act
OPNAV	Office of Naval Operations
OS	Operator Specialist
OV	Over View
Pde	Probability of decision error
PEO	Program Executive Office
PEO C4I	Program Executive Offices Command, Control, Communications, Computers, and Intelligence
PEO IWS	Program Executive Office Integrated Warfare Systems
Qd	Quality of decision
R2	Reporting Responsibility
RFI	Radio Frequency Interference
SA	Situational Awareness

SAG	Surface Action Group
SEDP	System Engineering Design Process
SOA	Service Oriented Architecture
SPAWAR	Space and Naval Warfare
TAO	Tactical Action Officer
TDS	Tactical Display System
TTWCS	Tactical Tomahawk Weapon Control System
UICS	Unique Interface Correlation Server
USCG NAVCEN	United States Coast Guard Navigation Center
USMA	United States Military Academy
UV	Utility Value
VSD	Value System Design

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